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Environmental Security Technology Certification Program (ESTCP)

Kinetic Super-Resolution Long-Wave Infrared (KSR LWIR) Thermography Diagnostic for Building Envelopes

Scott AFB, IL

James P. Miller and Navi Singh

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Abstract

Each year, U.S Air Force buildings waste millions of dollars' in energy lost through leaks in building envelopes. Identifying the source of this wasted energy has historically been time consuming and prohibitively expensive for large-scale energy analysis. This work used an independently developed drive-by thermal imaging solution that can enable the Air Force to achieve cost-effective energy efficiency at much greater scale than other commercially available techniques of measuring energy loss due to envelope inefficiencies from the built environment. A multi-sensor hardware device attached to the roof of a customized vehicle was used to rapidly scan hundreds of buildings in a short period of time.

At Scott Air Force Base, the unit identified over 3,000 distinct building feature components (doors, windows, soffits, etc.) on buildings across the base. These features were categorized by type and surface temperature to provide an in-depth analysis of each building's envelope energy profile. This report includes an in-depth analysis of 30 buildings at this installation, recommends specific energy conservation measures (ECMs), and quantifies significant potential return on investment.

Executive Summary

Each year, millions of dollars' worth of energy leaks from the envelopes of U.S. Air Force buildings due to missing or improperly installed insulation, cracks around doors and windows, thermal bridges in wall systems and many other deficiencies. Identifying the sources of this wasted energy has historically required manual thermal audits that are typically inconvenient, time consuming, and prohibitively expensive for large-scale energy analysis. Meanwhile, Federal agencies are under immense pressure to dramatically reduce the amount of energy consumed by their buildings.

This project demonstrated a unique drive-by thermal imaging process that enables cost-effective energy efficiency surveys of building envelopes at a much greater scale than other commercially available techniques of measuring energy loss due to thermally inefficient building envelopes. This solution used a multi-sensor hardware device mounted on the roof of a customized vehicle to rapidly scan hundreds of buildings in a short period of time. The gathered data were processed and analyzed at the contractor's (Essess, Boston, MA) headquarters to ascertain important building envelope information. This project demonstrated this technology by scanning U.S. Marine Corps Base Camp Lejeune, NC (American Society of Heating, Refrigerating, and Air-Conditioning Engineers [ASHRAE] Climate Zone 3) and Scott Air Force Base, IL (ASHRAE Climate Zone 4) to determine the amount of energy being lost at each installation due to thermally inefficient building envelopes.

A primary objective of this work was to compare this drive-by thermal imaging process with the conventional thermal imaging process using a handheld infrared camera. The hypothesis being tested was that the drive-by thermal imaging method is much faster, more accurate and more cost effective than traditional handheld thermal imaging methods.

For comparison purposes, the contractor team scanned at least six buildings at each installation using a FLIR i7 handheld thermal camera. The FLIR i-Series cameras are specially designed for building diagnostics and commonly used in residential and commercial thermal audits. The scanned images for these cameras are 140x140 pixels with a 29-degree by 29-degree field of view (FOV). The FLIR i7 camera uses a Spotmeter to detect the maximum and minimum temperatures within an image. The contractor found that each of the buildings scanned by the handheld method required about 25

minutes of imaging work. This method requires extra effort to manually overlap building components in each frame.

No effort was made to analyze the thermal image data captured by the handheld camera because such an analysis would have required all images to be stitched together which would have been a prohibitively time consuming effort and would have yielded somewhat uncertain results since they would have required a good deal of analyst interpretation.

By comparison, the contractor's kinetic super-resolution long-wave infrared (KSR LWIR) method used an integrated camera system that captures 640x512 pixels per frame for a 45-degree x 37-degree FOV. Computer vision calculated the temperature of each feature within the image and obtains material emissivity. Using the KSR LWIR drive-by method, it took about 30 seconds to scan each of the 12 buildings (i.e., six buildings at each installation) in the set that were also scanned by the handheld method.

Table ES-1 lists a number of the more significant performance objectives of this project including metrics, data requirements, success criteria and results.

The Table ES-1 results show that the drive-by method satisfied its performance objectives for Rapid Scanning and Rapid Analysis with over 100 buildings scanned per hour and the thermographic image data was analyzed at a rate of approximately 327 buildings per hour. This is at least an order of magnitude faster than could be achieved with handheld thermographic methods.

Table ES-1. Summary of performance objectives.

Performance Objective	Metric	Data Requirements	Success Criteria	Results
Quantitative performance objectives				
Rapid scanning	Buildings scanned per hour	Number of Buildings scanned and required time	> 100 Buildings per hour	*Scott AFB:* 327 buildings scanned at approx. 109 buildings scanned per hour *Camp Lejeune:* 1,307 buildings and other objects (Objects being sheds and unmanned buildings) scanned at a rate of approx 110 objects per hour
Rapid analysis	Buildings per hour	Number of Buildings analyzed and required time	> 50 Buildings per hour	Approx. 327 buildings per hour for both Scott AFB and Camp Lejeune

Performance Objective	Metric	Data Requirements	Success Criteria	Results
Cost effectiveness	Cost ($) for square footage of building scanned and analyzed/reported	Scanning, analysis and reporting costs for various numbers of Bldgs, similar costs for handheld methods	Cost below handheld methods for scanning 1million sq ft of building space or more, Simple payback = 10 years. (Since buildings can vary from a few hundred to several thousand square feet, total building square feet was used as a metric to measure the cost effectiveness of handheld versus mobile thermal imaging)	*Scott AFB:* Handheld thermography audits would have cost an estimated $920,000 based on 4.6 million sq ft scanned.. Essess costs for Scott AFB were approx. $200,000. *Camp Lejeune:* Handheld thermography audits would have cost an estimated $840,000 based on 4.2 million sq ft scanned. Essess costs for Camp Lejeune were approx. $200,000

Technology description

The technology being demonstrated consisted of a custom-built multi-sensor hardware device attached to the roof of a customized vehicle to rapidly scan hundreds of buildings in a short period of time. The gathered infrared imagery data were merged with light detection and ranging (LIDAR) data, Geographic Information System (GIS) data, and Global Positioning System (GPS) data and were then processed and analyzed at Essess headquarters to ascertain important building envelope information.

Demonstration results

At Scott AFB, over 3,000 distinct building feature components (doors, windows, soffits, etc.) were identified on buildings across the base. These features were categorized by type (e.g., brick wall, roof, window glass, window frame) and by surface temperature to provide an in-depth analysis of each building's envelope energy profile. This report (Appendix D) includes an in-depth analysis of 30 buildings selected by the installation and provides a breakdown of recommended energy conservation measures (ECMs) and the potential return on investment associated with implementing these recommendations. Essess' analysis showed that over $300,000 in potential envelope-related savings per year could be achieved by implementing various envelope-related ECMs. Over the lifetime of these measures, Scott AFB has the potential to save over $4 million by investing around $2 million with a simple payback period of roughly 7 years.

At Camp Lejeune, over 2500 distinct building feature components were identified across various buildings throughout the base. Similar to Scott AFB, these features were categorized by type and surface temperature to provide an in-depth look at the energy efficiency of each building's envelope. This quantified analysis showed that Camp Lejeune could save over $100,000 per year by implementing ECMs outlined in this report. The total investment would be less than $1 million, but would allow the base to save nearly $1.7 million over the lifetime of the measures with a simple payback period of less than 9 years. For both installations, the analysis assumes a cost per kWh of $0.056 and cost per therm of $0.59. The results of a detailed thermal analysis of 30 buildings from Camp Lejeune, including a breakdown of the most notable leaks for each building and remediation recommendations, is available in the Environmental Security Technology Certification Program (ESTCP) Final Report[1].

The contractor team found that commercial energy audits that include envelope thermal imaging using handheld thermography typically cost around $0.20/sq ft of building area (based on data from local thermal imaging auditors within 100 miles of Scott AFB and Green-Buildings.com). Based on the area of buildings scanned at Scott AFB (4.6 million sq ft) and Camp Lejeune (4.2 million sq ft) using the drive-by method, scanning these building using handheld thermography would have cost approximately $920,000 and $840,000, respectively, using the handheld method.

Essess' costs to scan, analyze and report results for each installation was ~$200,000 regardless of actual square footage scanned. By comparison, the drive-by thermal imaging was found to be much more cost effective than handheld scanning methods.

Implementation issues

Although both Scott AFB and Camp Lejeune have a positive return on investment (ROI), this research showed that Scott AFB has a higher potential savings threshold. This is believed to be due to the fact that Scott AFB is located in ASHRAE Climate Zone 4 which is a colder location than Camp Lejeune (ASHRAE Climate Zone 3).

[1] Final Report: ESTCP Energy and Water Project EW-201241, Kinetic Super-Resolution Long-Wave Infrared (LWIR) Thermography Diagnostic for Building Envelopes, February 2015.

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Preface

Funding for this demonstration was provided by the Environmental Security Technology Certification Program (ESTCP) under Military Interdepartmental Purchase Requests (MIPRs) No. W74RDV40212876 and No. W74RDV33512272 under FY12 Energy and Water Project EW-201241, "Kinetic Super-Resolution Long-Wave Infrared (LWIR) Thermography Diagnostic for Building Envelopes." The ESTCP technical monitor was Scott Clark.

The work was managed by the Energy Branch (CF-E) of the Facilities Division (CF) of ERDC-CERL. The ERDC-CERL Principal Investigator was James P. Miller, CEERD-CF-E. The work, including scanning of buildings at Scott Air Force Base, IL, analysis of data and reporting of results was performed by Essess, Boston, MA, under U.S. Army ERDC-CERL contract W9132T-14-C-0002. The following persons and organizations are gratefully acknowledged: (1) The Essess team (Boston, MA), who performed this work under ERDC contract W9132T-14-C-0002, in particular, Mr. Navi Singh, Head of Solutions Delivery, and Mr. Tom Scaramellino, President & Chief Executive Officer, for their tireless efforts and "can do" attitude that helped them to overcome various technical and administrative hurdles to bring this project to a successful conclusion; (2) personnel from Scott Air Force Base, IL, especially Elizabeth Toftemark for all of her help in scanning Scott AFB. At the time of publication, Mr. Andrew Nelson was Chief, CEERD-CF-E; L. Michelle Hansen was Acting Chief, CEERD-CF; and Kurt Kinnevan, CEERD-CV-T was the Technical Director. The Deputy Director of ERDC-CERL was Dr. Kirankumar V. Topudurti and the Director was Dr. Ilker R. Adiguzel.

COL Jeffrey R. Eckstein was Commander of ERDC, and Dr. Jeffery P. Holland was the Director.

1 Introduction

1.1 Background

According to the FY2012 Base Structure Report, the Department of Defense (DoD) has an existing inventory of 298,897 buildings comprising 2,300 million sq ft. These buildings represent almost every known facility type and range in age from recently constructed buildings to historic buildings more than 100 years old. The size and diversity of this building inventory makes it very difficult to identify and prioritize opportunities to improve building envelopes to reduce energy losses to the exterior ambient environment. It also makes it difficult to verify that building envelope repair/improvement projects have achieved their desired results.

Many Air Force installations are on a scale comparable to villages or small cities, with hundreds or thousands of facilities of various types and ages. Quality and condition of the building envelopes typically range from good to very poor. For most installations, there is significant opportunity to reduce installation energy consumption by identifying and prioritizing opportunities to improve the thermal performance of building envelopes.

Many installations have used infrared thermography as a tool to help identify buildings that have significant energy loss through the building envelope and to pinpoint specific problems on existing building envelopes that might be good candidates for repair or improvement. The U.S. Army Corps of Engineers (USACE) requires infrared scanning of newly constructed buildings prior to turn over to the customer. Unfortunately, although the current state of the handheld thermography technology produces reasonably good results, it is very time consuming to implement. Due to the number of facilities at most Air Force installations, it would be a formidable task to scan more than a small fraction of the facilities. Post-scanning analysis is also very time intensive and highly dependent on the skill of the individuals operating the infrared (IR) camera and interpreting the data. As a result, handheld infrared scanning and analysis methods are too time consuming, not cost effective for large numbers of buildings, and may yield questionable results.

This project demonstrated a capability to quickly diagnose the condition and thermal performance of building envelopes using kinetic super-resolution long-wave infrared (KSR LWIR) thermography to help the Air Force identify and implement opportunities to improve the thermal performance of its existing building inventory. The work was conducted at Scott Air Force Base, IL. It demonstrated a method of rapidly scanning and analyzing many facilities in a few hours which is far more efficient and cost effective than current methods involving manual infrared thermographic scanning and analysis of facilities. This method produced an accurate and actionable assessment of the assessed installations' facilities that will allow Scott AFB Civil Engineers to optimize use of their limited funds to repair or upgrade building envelopes to reduce installation energy consumption.

1.2 Objectives

The objectives of this demonstration were to:

- *Validate*. This project validated a method of rapidly and cost effectively scanning and analyzing large numbers of building envelopes, quantifying energy losses, and prioritizing energy leaks for cost-effective repairs or improvements.
- *Provide Findings and Guidelines*. This project demonstrated a process by which Civil Engineers can cost effectively evaluate large portions of their building stock to determine the overall condition of their building envelopes and identify opportunities to repair or improve the envelopes to reduce unnecessary energy losses and improve overall energy efficiency.
- *Accomplish Technology Transfer*: The Essess imaging rig was deployed based on a licensing model so there was no turnover of hardware, software, or intellectual property to the Government. However, Air Force installations can access this technology by directly contracting with Essess.
- *Facilitate Acceptance*: This technology is currently marketed as a service to the utilities industry. Essess supports the energy conservation programs of utilities by performing drive-by scanning of large portions of their service areas. This can entail performing scans of tens of thousands of residential or commercial structures. The system software automatically analyzes the thermal imagery and provides a custom report for each building that recommends cost-effective measures to improve

comfort, save energy and lower utility costs. In some cases, the utilities may offer the homeowners subsidies or incentives to motivate adoption of recommended measures. Essess may also perform follow-up scans several months after an initial scan to verify that homeowners actually made improvements for which they claimed a credit. In a similar fashion, this technology is a useful tool that can help Air Force Civil Engineers evaluate the effectiveness of building repair and renovation projects, and determine if the energy performance of new buildings complies with design requirements.

1.1 Regulatory drivers

Air Force Civil Engineers face a major challenge of complying with numerous Executive Orders (EOs), statutes and DoD/Air Force policies mandating energy consumption reductions in a business climate of reduced installation budgets and manpower. Use of this demonstrated technology may help Air Force Civil Engineers comply with the following regulatory drivers:

- *EO 13423 (2007), Strengthening Federal Environmental, Energy, and Transportation Management.* This EO requires Federal agencies to reduce energy use by 20% below their 2003 baseline energy consumption. Reduced energy losses through building envelopes will help installations move toward their energy reduction targets.
- *EO 13514 (2009), Federal Leadership in Environmental, Energy and Economic Performance.* This EO mandates that all new construction, major renovations, or repairs/alterations of Federal buildings comply with the implications of The Guiding Principles for Federal Leadership in High Performance and Sustainable Buildings (Guiding Principles). The Guiding Principles focus on the following five topic areas for both new construction and major renovations:
    - Employ integrated design principles (new construction)/Employ integrated assessment, operation, and management principles (existing buildings)
    - Optimize energy performance
    - Protect and conserve water
    - Enhance indoor environmental quality
    - Reduce environmental impact of materials
- Of these topic areas, the first two might be applicable if the results of a thermographic survey provided an impetus to execute a major renovation of one or more existing buildings.

- *Energy Independence and Security Act of 2007 (EISA 2007)* requires Federal agencies to conduct and document an energy survey of 100% of their "covered facilities" every 4 years. Although a thermographic survey by itself would not satisfy the EISA 2007 energy survey requirements, it would improve the overall quality of an EISA 2007 survey by providing a quality assessment of the condition of building envelopes.
- The *U.S. Air Force Energy Strategic Plan (March 2013)* states that the Air Force is pursuing a net zero posture for installation energy and water to help achieve the Federal goal of zero net energy by 2030 for all new facility construction and alterations.
- Use of this technology may help Air Force Civil Engineers to reduce overall energy use and maximize energy efficiency by identifying and remediating significant energy leaks in existing buildings as part of their operations and maintenance (O&M) program. It may also help installation planners by helping them recognize buildings with such poor building envelopes that a major renovation or outright replacement of the building would be warranted.

1.2 Approach

The objectives of this work were accomplished in the following steps:

1. A kickoff phonecon was conducted with Energy Managers at Scott AFB on Friday, 7 February 2014.
2. Scanning activities were conducted at Scott AFB from 28 February to 1 March 2014.
3. Collected data were imported into a secure data storage system located at the contractor's headquarters facility, where the import agent program ran a more rigorous data quality filter.
4. The results were analyzed, conclusions were drawn, and installation-specific recommendations were formulated.

1.3 Scope

Although the results of this work pertain specifically to Scott AFB, IL, the technology application is considered broadly applicable to other Air Force installations.

1.4 Mode of technology transfer

This work demonstrated a capability to quickly and cost effectively perform and analyze scans of Air Force installations to identify and prioritize candidate buildings that might benefit from building envelope repairs/improvements. The resulting data will help Air Force Civil Engineers to improve the energy performance of their facilities, to reduce energy consumption and utility costs, and to meet mandated energy reduction goals. This project did not transfer hardware, software, or intellectual property to the Government. However, Air Force installations can access this technology by directly contracting with Essess.

2 Technology Description

2.1 Technology overview

2.1.1 Description

Long-wave infrared (LWIR) cameras are regularly used in conjunction with building audits to identify thermal leaks in building envelopes. Referred to as “infrared thermography,” the technology allows the observer to “see” heat escaping from (or entering) specific areas of buildings. Because objects emit LWIR radiation in wavelengths that vary with their temperature, infrared thermography can help detect problems invisible to the naked eye, including missing, damaged, or improperly installed insulation within walls and roofs, thermal bridges, poor seals, etc. For example, most thermal bridges have a distinctive spatial signature that yields a thermal image with relatively uniformly warm areas surrounded by relatively uniformly cooler areas, separated by a very steep temperature gradient. This data, captured from the street, can be used to locate thermal leaks, determine their extent and, after analysis, their probable underlying cause(s).

Essess is a hardware and software technology company that has developed drive-by thermal imaging capabilities that enable public utility and Government clients to identify energy waste in buildings at an unprecedented scale. In the context of utility projects, the thermal images can be leveraged to deliver the Thermal Analysis Program, an energy efficiency program that helps public utilities meet mandated state energy efficiency goals by guiding building owners through the process of remediating sources of energy waste. For Government and military projects, the thermal images enable the system to generate a complete analysis of energy waste across the entire building stock, empowering Government and military clients to allocate energy efficiency investments and resources optimally and with greater confidence around the return on investment (ROI).

For military installations, Essess focuses on building envelope analysis and actionable recommendations based on envelope ECMs. A single thermal imaging rig can analyze thousands of buildings in a single night depending on building density and other factors, enabling the system to deliver energy waste intelligence at an order of magnitude greater scale than current approaches. The patent-pending technology stems from cutting edge research conducted in the Field Intelligence Laboratory at the Massachusetts Institute of Technology (MIT).

This drive-by system uses specially equipped vehicles operating on streets and roadways to capture a 3D thermal video of the surrounding environment. The actual imaging system is a custom-designed multi-sensor rig mounted on the roof of the vehicle. As the vehicle drives, the imaging rig captures the scene on both sides of the car, enabling the system to image large geographic areas each night. The images are stored onboard the vehicle using a custom-built data recording system and then processed at Essess' headquarters in Boston, MA. Before analysis, the data are uploaded to Amazon Web Services (AWS) servers housed in nondescript facilities. AWS data centers have industry leading security to ensure the data are protected by military grade perimeter control with state of the art intrusion detection systems.

In an IR thermal image, the brightness of an area indicates its relative energy loss. The brighter the area, the more energy is escaping. Common image patterns demonstrating substantial energy waste include bright yellow lines where siding meets a roof or a chimney, bright yellow or orange auras near foundations, and yellow auras or lines along window or door edges or around soffits. By contrast, a properly insulated building area will appear darker than the surroundings, most commonly blue or purple.

In the context of public utilities, this technology has the capability to generate complete thermal scans of entire utility service territories in a matter of days or weeks. This kind of unprecedented territory-wide analysis would take months or even years using traditional audits, and would likely be prohibitively expensive. This improved thermal scan methodology not only achieves this scale of operation more efficiently and cost effectively, but also with improved accuracy and reliability. While certain information can only be obtained through an in-home audit, the drive-by thermal imaging system provides comparable intelligence at an order of magnitude lower cost. Similar results can be expected for buildings on large Government installations. This kind of intelligence is invaluable in determining the buildings that follow-on auditors should survey and also as a prediagnostic to make the best use of the auditors' time on site.

2.1.2 Components of the system

The drive-by thermal imaging vehicles are equipped with the following components:

- Multi-spectral infrared imaging of structures, including:
  - Long-wave infrared (LWIR) radiometric cameras
  - Near infrared (NIR) high dynamic range cameras
  - NIR scene illumination for rural and poorly lit suburban regions
  - Capture of thermal signatures of structures
- Building facade discovery and background removal capabilities using computer vision and machine learning engines
- A camera housing offering 70 degree vertical FOV and full width horizontal FOV of structures due to vehicle motion
- Automated building detection capability within property boundaries, facilitated by:
  - A rotating laser array light detection and ranging (LIDAR) sensor which captures ranging and reflectance even from large standoff distances
  - A capability to isolate buildings from the scene using 3D LIDAR point clouds
  - A ranging capability which allows structures to be bounded within property lines and relevant locations
  - A mapping grade Global Positioning System (GPS) and support filtering algorithms which ensure highly accurate location of structures and properties
- Collected data used in simultaneous localization and mapping, which allows the system to supplement the GPS data captured and more accurately correlate each image to the relevant building.
- Highly reliable onboard data capture and diagnostics system, which includes:
  - Onboard data validation and recording software and hardware
  - Real-time diagnostic and quality control provided by Long Term Evolution (LTE) cell network streaming to Essess headquarters
  - A system that performs over a wide range of seasonal temperatures, down to at least -30 °C and up to above 40 °C
- A high mast that enables operation in a variety of regions, including short standoff distances with 3-4 story buildings.

Combined, these hardware and software capabilities constitute a highly effective way to capture heat loss and building envelope data via drive-by thermal imaging (Figure 1). Each camera captures data in a video format, meaning that the drive-by system generates hundreds of thousands of images comprising over 2 terabytes of data each night. The LIDAR sensors (Figure 2) enable the system to generate a 3D map of the physical environment and map buildings to parcels in a highly accurate manner. The proprietary hardware and software configuration enables the system to capture vast amounts of data and subsequently process that data in a very efficient and automated manner.

Figure 1. Specially equipped Essess scanning vehicle.

Figure 2. Contractor-developed scanning rig including GPS, long-wave infrared, near infrared and LIDAR instrumentation.

2.1.3 Comparison to existing technology

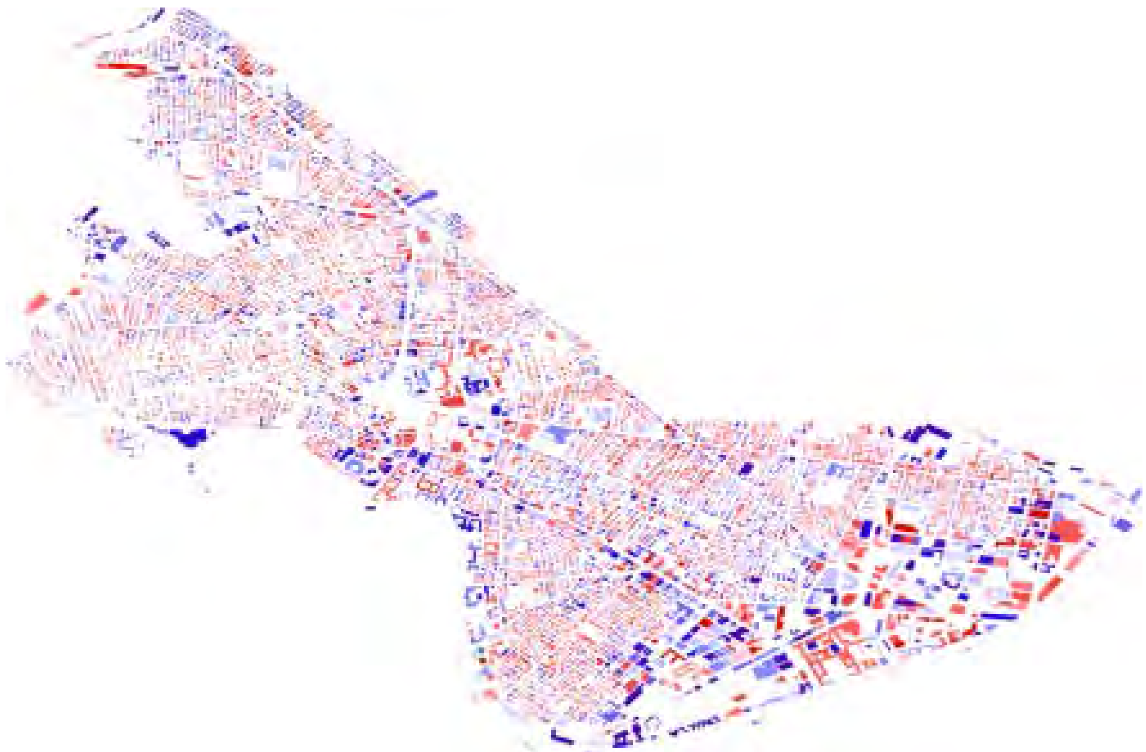
This technology is similar to handheld infrared scanning technology in that both methods use infrared photographic methods. Unlike handheld methods which record still images, this process captures video infrared images. This method combines video data with GPS data, LIDAR data, and GIS data (e.g., building size, building age, envelope materials) to permit rapid data analysis, including quantification and prioritization of envelope energy leaks and an analysis of cost-effective methods of repair and improvement. Essess normally acquires GIS data from private companies. For military projects, GIS data are acquired from the installation being scanned (billing was provided). Because this is a video process, it is capable of scanning many buildings in a short period of time. Handheld infrared imaging methods would require many work-hours to achieve the same results.

- *Future Potential for the Air Force*. This technology may prove to be a useful aid in O&M of facilities and in installation planning. Energy leaks identified using this technology can be analyzed and prioritized for the most effective use of O&M dollars. An installation's inefficient facilities can be identified and a cost associated with their condition can be used in prioritizing buildings for repair, major renovations or outright replacement.
- *Anecdotal Observations*. The heat map of thermal imaging data collected from Cambridge, MA, (Figure 3) shows a distribution of blue (efficient building envelopes) and red (inefficient building envelopes) buildings. In certain cases buildings of similar vintage, square footage, location, and style have very different envelopes in terms of energy efficiency. This suggests that there are numerous instances where thermal imaging data may very well be the main differentiating factor in determining building envelope quality between two otherwise similar structures, even for cases where only one side of the building is visible from the street.

2.1.4 Energy analysis architecture

This "Essess Energy Analysis Architecture" is a unique hardware and software approach which develops very specific remediation recommendations to increase building energy efficiency. In the context of work in support of public utilities, it begins by combining scanning data with GIS data, public property records (for private sector residential buildings), and information on construction material properties, and produces building-specific energy reports and/or a region-wide energy analysis.

Figure 3. Building envelope efficiency map of over 17,000 buildings in Cambridge, MA.

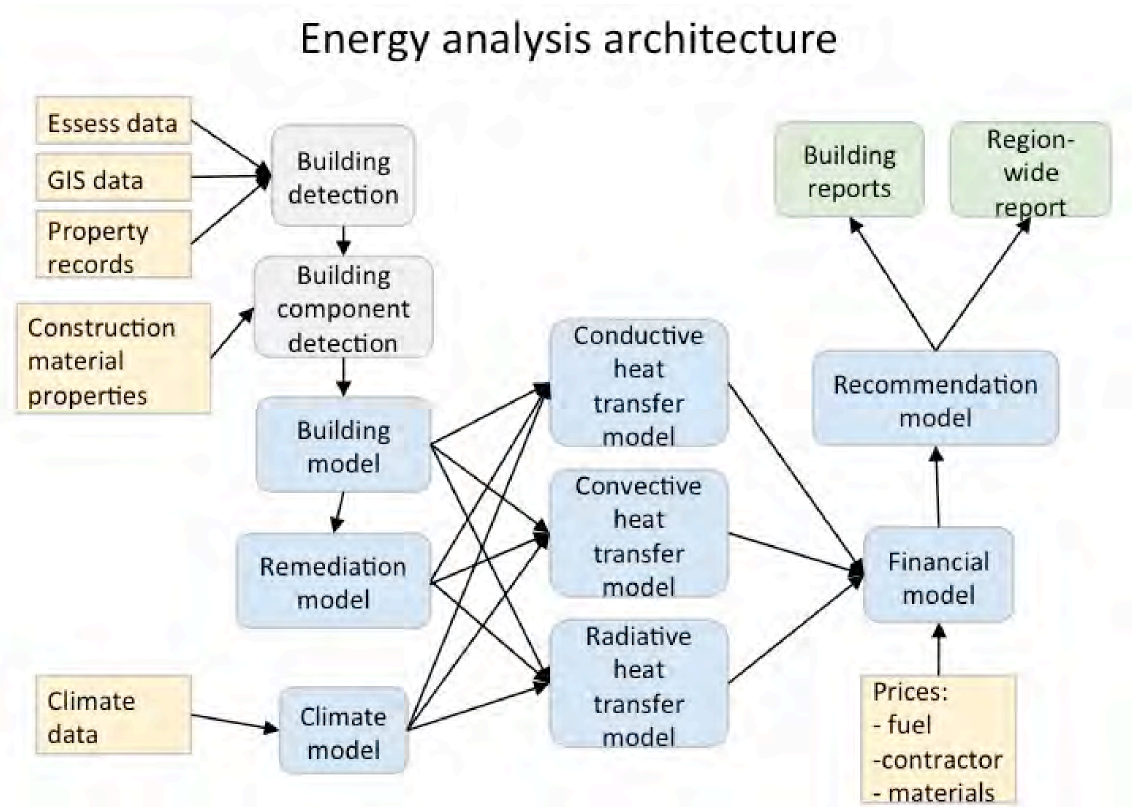


After the system scans a specific area, each scanned building is matched with its corresponding address or geographical location (latitude and longitude). Once a building has been detected and correlated to the correct address or building number, the construction material library, a database containing information on the emissivity of various types of materials, is used to differentiate, for example, a building's window from a door. This phase is referred to as "building component detection." It allows the algorithms to identify windows, doors, and other features of the building. Once a building and its building components are detected, those data are used to build a model to automatically detect similar buildings and similar building components in comparable datasets. These data are combined with a Remediation Model to automatically detect the building components that may need attention, and with a Climate Model to determine the weather-related variables of the scanning data. The Building Model, the Remediation Model, and the Climate Model are then used to develop a Conductive Heat Transfer Model to identify conductive leaks, a Convective Heat

Transfer Model to identify convective heat loss, and a Radiative Heat Transfer Model to identify thermal radiation heat loss. The Conductive, Convective, and Radiative Models provide heat loss data that can then be combined with fuel prices, and labor and materials costs in the Financial Model. The Financial Model quantifies the energy loss and the potential dollars that can be saved by preventing the identified heat loss. Correlating the potential savings to specific fixes (Remediation Recommendation Model) allows the system to recommend the energy efficiency remediations that have the best ROI.

Figure 4 shows the Energy Analysis Architecture breakdown.

Figure 4. Schematic breakdown of the Essess Energy Analysis Architecture.



2.2 Technology development

Essess is unique in the thermal imaging space as it is the only company in the world with the ability to scan thousands of buildings using a proprietary hardware device comprised of multiple sensors and a capability to process and analyze that data in a completely automated way. The hardware, comprised of the physical sensors on top of the vehicle, and the software which processes and analyzes the collected data are both based on research conducted at the Field Intelligence Lab at the MIT. Dr. Sanjay Sarma, Professor of Mechanical Engineering, recruited leading scientists and thought leaders to study the viability of remote, high-throughput thermal imaging at scale and develop techniques for identifying and assessing energy waste on a large scale.

The practical applications of high-throughput thermal imaging were researched and studied for multiple years before a prototype was built. The first imaging rig was tested in Cambridge, MA, and the data were analyzed to create a heat map overview of the city as shown in Figure 3. The rapid scanning methodology and processing of imaging data were also demonstrated at Fort Drum, NY in February 2011.

After years of research and development and millions of dollars invested, Essess developed the current imaging rig which uses cutting edge technology to gather terabytes of data on a nightly basis. The custom hardware is augmented by advanced software algorithms that process the data. The system uses advanced machine learning and computer vision algorithms to scale up thermal imaging and processing to overcome the small-scale limitations of traditional infrared thermography which uses handheld cameras and requires manual analysis of each individual image.

2.3 Advantages and limitations of the technology

2.3.1 Performance advantages

This technology may improve energy efficiency by enabling Air Force Civil Engineers to cost effectively scan and analyze most or all of the building envelopes on their installations to identify and prioritize the most significant energy leaks and to implement measures that repair or improve existing building envelopes or identify and prioritize buildings that warrant major renovations or outright replacement. With handheld thermography methods, it would be too costly and time consuming to perform infrared scans and analyze the data for large numbers of buildings.

2.3.2 Cost advantages

For large sets of buildings, this technology should be much more cost-effective than traditional handheld methods of performing infrared thermography scanning and analysis of buildings. Handheld IR scanning methods are much more time consuming, resulting in significant added labor costs.

2.3.3 Performance limitations

This technology is limited to scanning the street sides of buildings. As a result, for most buildings, four sides of the buildings will not be scanned. Two or three sides are typically scanned depending on the orientation of a building relative to the street. This technology is also limited by the requirement to have a minimum ΔT between building interior and exterior ambient temperatures of at least 20 °F, so scanning must occur when nighttime temperatures are below 50 °F. This limits application of this technology to regions where there is at least 1 week of the year in which nighttime temperatures are below 50 °F. Most regions of the United States fall within this boundary condition. Adjustments are made for empty buildings or buildings where there is no internal heating and no way of knowing the internal temperature setpoint (discussed in Section 4.3.3). This technology is somewhat hindered by trees, bushes and other obstructions that might partially obscure a clear view of a building's envelope from the street. However, the automated data processing pipeline developed by Essess to take the scanned data and prepare it for a report format corrects for these kinds of obstructions in a number of ways that have been tested by Essess.

2.3.4 Cost limitations

There is a lower limit of the number of buildings that can be cost effectively scanned and analyzed by this method. Below this limit, it is more cost effective to identify and analyze building envelope energy leaks by another method. This demonstration sought to determine this cutoff point. As referenced in Table 2. *Performance Objectives*, the average cost for performing a handheld thermal audit on a 5,000 sq ft commercial building is approximately $1000 (or $0.20 per sq ft). Considering Essess charges approximately $200,000 per installation, it would be beneficial to perform an Essess scan for any installation that has at least 1 million sq ft in buildings (determined by adding the individual square footage of each building scanned). For perspective, over 4.6 million sq ft of buildings were scanned at Scott Air Force Base.

It was also considered desirable to document the cost structure of this technology to help Air Force Civil Engineers determine how the technology might fit within the constraints of their business process. For example, this technology is able to capture scan data on hundreds or thousands of buildings in a very short period of time such that very large installations could be scanned within a matter of days. The resulting marginal cost of scanning buildings is relatively inexpensive. However, the process of analyzing scan data to identify and prioritize energy leaks is more challenging and has a significantly higher marginal cost. Since both of these processes must be done together to provide a military installation with actionable results, documenting the cost structure for these services will help Facilities Engineers determine how they might benefit from Essess thermal imaging.

Table 2. Summary of performance objectives.

Performance Objective	Metric	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives				
Rapid scanning	Buildings scanned per hour	Number of Buildings scanned and required time	> 100 Buildings per hour	*Scott AFB:* Approx. 109 buildings per hour for a total of 327 buildings (Based on building density of Scott AFB, rig setup and resting period. Total imaging time of 3 hr, 0 min with 52 min of rig setup, calibration, travel time, and resting period.)
Rapid analysis	Buildings per hour	Number of Buildings analyzed and required time	> 50 Buildings per hour	Approx. 327 buildings per hour for both (leaks identified as polygons and subsequently analyzed)
Actionable results	Building envelopes determined to be adequate (needing no improvements) or improvement projects scoped for envelopes having identified deficiencies	Number of envelopes deemed adequate and/or having projects scoped to correct identified deficiencies	For Scott AFB, the envelopes of at least 25 of the 30 buildings selected for detailed analysis were deemed to be adequate or had projects identified to correct deficiencies	392- Window Frames 97- Door Frames 686- Walls 170 – Roofs 241- Soffits See Chapter 5 (Performance Assessment) for more detail.
Cost effectiveness	Cost ($) for square footage of building scanned and analyzed/reported.	Scanning, analysis and reporting costs for various numbers of Bldgs, similar costs for handheld methods	Cost below handheld methods for scanning 1 million sq ft of building space or more, Simple payback = 10 years. (Since buildings can vary from a few hundred to several thousand square feet, total building square feet was used as a metric to measure the cost effectiveness of handheld versus mobile thermal imaging)	*Scott AFB:* Handheld thermography audits would have cost an estimated $920,000*. Essess costs for Scott AFB were approx. $200,000.
Qualitative Performance Objectives				

Robust technique within defined range of operating conditions	High quality scanned imagery	Scan data quality under a range of environmental operating conditions	"High Confidence**" in results obtained within defined limits	Success: Within the defined range of operating conditions, the thermal imaging system is capable of capturing high quality data that can be analyzed for envelope issues.
Comparing the fidelity and usefulness of imagery at varying scanning distances	Measuring the image quality of data taken at varying distances starting at 20 yds and ending at 180 yds with 20 yd intervals	Thermal images taken by mobile imaging rig at 20 yd intervals from 20 to 180 yds	"High Confidence"** that the temperature data can be seen at extreme distances	The results show that infrared imaging is capable of capturing temperature data at 180 yds. However, the number of pixels in the frame limits the data quality.
Street-side scanning sufficient	Representativeness of street-side sample vs. 360-degree scan of building using handheld methods	Street-side drive-by scan results and 360-degree handheld scan results	"High Confidence"** that results of street-side scans adequate for planning purposes	Street-side data is representative of sides not seen from the street
Ability to usefully scan Bldgs obscured by wall of trees and other obstructions	Data loss due to obstructions	Leaks obscured by obstructions	"High Confidence" that obstructions do not appreciably impact results	Line-of-sight between imaging system and building is required for data capture. The imaging rig is able to capture data when driving by a single tree or utility pole, but is unable to capture data when the building is completely blocked from the imaging rig (i.e., with a fence, multiple trees, etc.).

* Commercial energy audits that include envelope thermal imaging using handheld thermography can typically cost around $1,000 for a 5,000 sq ft. building and $10,000 for a 50,000 sq ft. building (based on data from thermal imaging auditors within 100 miles of Scott AFB and Green-Buildings.com). At Scott AFB, Essess imaged 4.6 million sq ft and 278 buildings. Unlike a typical auditor that charges per building, Essess' cost structure is on a per installation basis. This is due to the fact that the bulk of Essess' costs are front-loaded. Once the imaging rig is deployed to an area, there is only a marginal cost in imaging 1,000 buildings versus 100 buildings.

** "High Confidence" is based on a visual examination by an Essess scientist resulting in a determination that the data can be used for performing an analysis of the building envelope.

2.3.5 Social acceptance

There were no problems associated with social acceptance by installation staff. This technology had little or no impact on the activities or processes of the installation. On-site activities were conducted at night when very few installation operations were occurring. The only burden placed on installation personnel was the need for them to provide installation GIS data and energy data for analysis requirements. The GIS data were a necessary component of the scanning process as they allowed Essess to correlate the scanned image of a building with the building's exact geographical location. The energy data allowed Essess to calibrate the results of the thermal envelope analysis.

2.3.6 Description of performance objectives

Rapid Scanning:

- *Definition*. This performance objective measured how rapidly buildings can be scanned.
- *Purpose*. The purpose was to compare the speed of the demonstrated method of drive-by scanning to conventional handheld methods. In terms of speed, the drive-by method was orders of magnitude faster, which translates into an ability to scan more buildings and to minimize the scanning contractor's time on the installation and associated impact on installation personnel and operations. A detailed comparison of handheld versus drive-by scanning is provided later in this report.
- *Metric*. The metric was buildings scanned per hour.
- *Data*. Number of buildings scanned and duration of scanning operations.
- *Analytical Methodology*. A simple count of the number of buildings scanned and the elapsed time of the scanning activities.
- *Success Criteria*. Objective successfully met — Greater than 100 buildings scanned per hour.

Data Analysis:

- *Definition*. This performance objective measured how rapidly buildings could be analyzed.
- *Purpose*. The purpose was to determine whether the demonstrated method of automated data analysis could analyze 50 or more buildings per hour.
- *Metric*. The metric was buildings analyzed per hour.

- *Data*. Number of buildings analyzed and time required to analyze the scanned buildings.
- *Analytical Methodology*. A simple count of the number of buildings analyzed and the amount of time required to analyze these data.
- *Success Criteria*. Objective successfully met — greater than 50 buildings analyzed per hour.

Actionable Results:

- *Definition*. This performance objective measured the effectiveness of this process by validating the condition of building envelopes needing no repairs or upgrades and identifying projects to improve envelopes that are not deemed adequate.
- *Purpose*. This metric was intended to focus the demonstration on developing results that help Air Force Civil Engineers determine whether or not the installation's stock of building envelopes are adequate and acceptable or, if not, by identifying projects to address identified deficiencies.
- *Metric*. Building envelopes determined to be adequate (needing no improvements) or improvement projects identified to bring the envelopes up to acceptable levels or performance.
- *Data*. Number of envelopes deemed adequate and/or having projects identified to bring the envelopes up to acceptable levels or performance.
- *Analytical Methodology*. Based on a count of the number of buildings that are evaluated as having acceptable building envelopes and/or the number of buildings for which projects are identified to bring the envelopes up to acceptable levels of performance.
- *Success Criteria*. Objective successfully met — For Scott AFB, the envelopes of at least 25 of the 30 buildings selected for detailed analysis were deemed to be adequate or to have projects identified to correct deficiencies.

Cost Effectiveness:

- *Definition*. This performance objective measured the economic value of this process to the installation.
- *Purpose*. Installation engineers and managers will only be interested in this technology if they perceive it to produce economic value. Considering the cost of drive-by scanning and analysis, and the cost of imple-

mentation of identified mitigation measures, the energy savings must be sufficient to warrant the investment.

- *Metric*. Dollars (marginal cost) per building scanned, analyzed and reported. Simple payback ((Cost of scanning + cost of repair) / annual energy cost savings).
- *Data*. Marginal scanning, analysis and reporting costs for various numbers of buildings and comparable data for similar services using the drive-by method and handheld thermography methods. Costs to execute repairs and estimated annual energy savings.
- *Analytical Methodology*. The methodology involves compiling the total costs of remediation of "feasible" fixes and the cost of conducting the drive-by scanning and the total anticipated energy cost savings. Feasible fixes were deemed to be those with a payback of 15 years or less.
- *Success Criteria*. Objective successfully met — The costs of scanning, analysis, and reporting are below the same costs incurred using handheld thermography methods for scanning 1 million square feet of buildings. (The simple payback should be 10 years or less.)

Robust technique within defined range of operating conditions:

- *Definition*. This performance objective measured the quality of scanned imagery within the prescribed operating conditions of this methodology.
- *Purpose*. The objective was to define a range of environmental conditions within which acceptable results can be expected.
- *Metric*. A qualitative assessment of image quality based on resolution and size of scene captured under ideal imaging conditions (i.e., temperature difference of 20 °F and no precipitation).
- *Data*. Mobile scan data quality under a range of environmental operating conditions.
- *Analytical Methodology*. Perform scans within recommended environmental operating conditions and scans at conditions outside the recommended range and compare results.
- *Success Criteria*. "High Confidence" in results obtained within defined limits. ("High Confidence" was based on image resolution and limitations on motion blur. Specifically, for images taken in recommended environmental operating conditions, the resolution should produce images with a resolution of 640 x 512 without motion blur or color saturation. During the demonstration, this performance objective was successfully met by analyzing each image for motion blur.

Comparing the fidelity and usefulness of imagery at varying scanning distances:

- *Definition*. This performance objective measures the image quality of data taken at varying distances starting at 20 yards and ending at 180 yards with 20-yard intervals.
- *Purpose*. The objective was to test how distance affected temperature reading from a thermal image when using mobile imaging system.
- *Metric*. Measuring the image quality of data taken at varying distances starting at 20 yards and ending at 180 yards with 20-yard intervals.
- *Data*. Thermal images taken by the mobile imaging rig at 20-yard intervals from 20 to 180 yards.
- *Analytical Methodology*. Perform scans with the mobile imaging rig at varying distances and compare results to determine the degradation in image quality as the distance is increased.
- *Success Criteria*. "High Confidence" that for results obtained at up to 180 yards, the imaging rig is capable of capturing useful temperature information. This performance was successfully met through a distance experiment conducted where the imaging rig was used to image a building from 20 yards all the way to 180 yards.

Sufficiency of Street-Side Only Scanning:

- *Definition*. This performance objective measured how well scanning of buildings from only the street side actually represents the overall condition of the building envelope.
- *Purpose*. The objective is to see how representative street-side only drive-by scanning is compared to 360-degree scanning. Since it will be impossible to drive all the way around many military buildings, it is useful to know how much one can depend on a scan on just the street side of the building.
- *Metric*. Representativeness of street-side sample vs. a 360-degree scan.
- *Data*. Street-side drive-by scan results and 360-degree handheld scan results.
- *Analytical Methodology*. For a small subset of six buildings, 360-degree drive-by scans were performed and those results were compared to the results of "street-side" only scans to estimate how much building information was lost by scanning the street side only.
- *Success Criteria*. "High Confidence" results from street-side scans adequate for planning purposes. This performance objective was based on the number and size of leaks on the street-facing wall compared to

those on the other walls not observable from the street. This objective was successfully met by analyzing the results from buildings imaged from the street versus buildings imaged from all sides using a handheld thermography camera. For the small subset of buildings scanned, the leak profile was consistent on all sides of the building envelope.

Ability to Usefully Scan Buildings Obscured by Trees and Other Obstructions:

- *Definition*. This performance objective measured how well the drive-by scanning process was able to accurately capture building envelope data for buildings that were obscured by trees, utility poles, and other obstructions.
- *Purpose*. Since many building facades will be partially obscured by utility poles, trees, shrubbery, and other obstructions, it is important to know how much value is lost due to such obstructions blocking a clear view of the building facade.
- *Metric*. The metric is the relative amount of data that are lost due to obstructions.
- *Data*. Lost data are measured in the number and severity of leaks obscured by obstructions.
- *Analytical Methodology*. Analysis involved a visual evaluation of energy leaks obscured by trees and other obstructions.
- *Success Criteria*. Objective successfully met. Success was judged in terms of “High Confidence” that obstructions do not noticeably impact results. This qualitative standard was based on the contractor’s experience with off-site tests with obstructions in the line-of-sight of LWIR cameras. The conclusion of this experiment was that the imaging system must have line-of-sight between the imaging sensors and the building being imaged to capture any useful temperature information.

3 Facility/Site Description

3.1 Facility/site selection criteria

3.1.1 Geographic criteria

The mobile scanning technology is relevant to climate zones where the heating season ΔT (indoor to outdoor temperature) can be expected to be at least 20 °F during the building scanning period. As a result, this technology may not be applicable to certain regions within Climate Zones 1 and 2. This demonstration selected installations in Climate Zones 3 (Camp Lejeune), and 4 (Scott AFB) and it is believed that there is great potential for use of this technology in Climate Zones 5 and above. Camp Lejeune and Scott AFB were chosen, in part, because they had a large number of significant buildings to scan to demonstrate this technology. This technology is also capable of capturing data during cooling season as long as the ΔT (indoor to outdoor temperature) is at least 20 °F.

3.1.2 Facility criteria

This demonstration worked with the installations to select buildings typical of modern installations. Buildings selected included command headquarters, dormitories, training facilities, admin facilities and similar large buildings. At each installation, a minimum of 250 buildings were scanned and a detailed analysis of 30 buildings, selected by the installation, was performed.

3.1.3 Facility representativeness

The installations selected are very large and had a full range of facility types and buildings of various vintages. The buildings and building types at both installations were quite representative of buildings that would be found at other military installations.

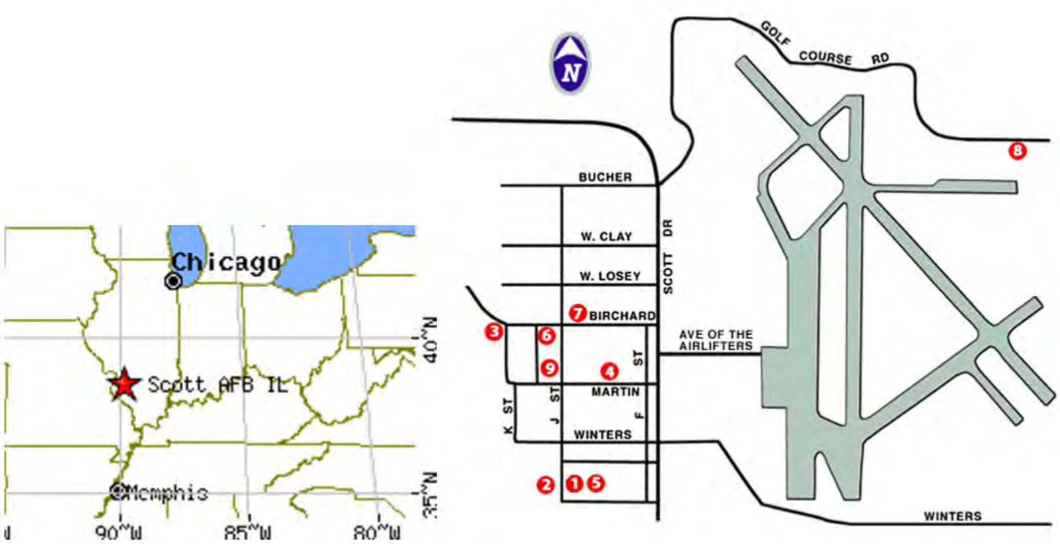
3.2 Facility/site location and operations

3.2.1 Demonstration site: Scott AFB, IL

Scott AFB is located approximately 20 miles east of St. Louis near Belleville and O'Fallon, IL (Figure 5) and is the home of the 375th Air Mobility Wing and host to 30 tenant units including: U.S. Transportation Command, Air Mobility Command, 18th Air Force, the 618th Air and Space Operations Center (Tanker Airlift Control Center), the Military Surface Deployment and Distribution Command, 932nd Airlift Wing (Reserve), 126th Air Refueling Wing (Air National Guard), the Air Force Network Integration Center, the Defense Information Systems Agency and the Defense Information Technology Contracting Organization, and the 635th Supply Chain Operations Wing (SCOW). Scott AFB has a broad range of facility types and a full spectrum of facility vintages from very old to very modern.

Scott AFB provides mission-ready Airmen and a broad range of critical capabilities. Since the on-site activities associated with this demonstration were short term, there was little or no interaction between this project and normal military activities.

Figure 5. General location (left) and installation map (right) of Scott AFB.



4 Test Design

4.1 Conceptual test design

4.1.1 Hypothesis

Compared to using traditional handheld thermography, the demonstrated drive-by thermal imaging technology gathers energy efficiency information from the building stock in a manner that is faster, more cost effective, and easier to scale.

4.1.2 Independent variable

The main independent variable being tested was the KSR LWIR imaging and analysis process.

4.1.3 Dependent variable(s)

Dependent variables measured included emissivity, building type, building square footage, and scene occlusion. Other variables tested during the demonstration process included:

- Scanning time (scanning time using a mobile imaging system versus scanning time using a handheld thermal camera to determine scalability in terms of time)
- The effects of resolution when scanning with the imaging rig versus scanning with a handheld camera to determine importance of image quality
- Scanned image quality from varying distances (specifically 20 meters, 50 meters, and 100 meters).

4.1.4 Controlled variable(s)

Controlled variables included the pre-selection of building types of similar size and building materials for scanning and analysis by both the drive-by and the handheld methods. Both scanning methods were conducted simultaneously to ensure identical temperatures and weather conditions during scanning operations.

4.1.5 Test design

The demonstration of the long-wave infrared (LWIR) imaging technology took place during February and March 2014. Over 250 buildings were scanned at Scott AFB using the thermal imaging rig. Six buildings were scanned at the installation using both the drive-by scanning rig and a traditional handheld thermal camera to set up the comparative analysis between the two methods of thermal data gathering. The conventional handheld scanning was carried out under the same weather and temperature conditions as the mobile imaging scan to ensure that the data being captured was comparable. All attempts were made to tightly monitor the controlled variables for both the imaging rig and the handheld scans. The scanning process began 2 hours after sunset and concluded 30 minutes before sunrise on nights with temperatures below 50 °F. The imaging rig captured and recorded data on hard drives that were mailed back to Essess headquarters for processing. Images were analyzed with respect to energy loss via infiltration, damaged building components, inadequate insulation, and thermal bridges. The imaging data was combined with GIS information, LIDAR data, and other building data. Note that thermal images taken with a handheld camera were not processed by automated methods, but were visually analyzed by a human auditor, making the process less efficient and more difficult to scale.

4.1.6 Test phases

The scanning activities conducted at Scott AFB were conducted in three phases.

4.1.6.1 Phase 1 – Planning and preparation

In preparation for scanning at Scott AFB, the imaging rig was customized specifically for gathering data on a military installation. For example, a distortion map was created for the near infrared (NIR) cameras, the NIR illuminator was adjusted for imaging buildings further back from the street than typical residential homes, the sweeping LIDAR was configured to compensate for poor street information, and the onboard GPS units were configured for optimal imaging in areas with low satellite access. The viewing angle for the entire hardware device was adjusted to optimally capture buildings larger than a typical residential home. A custom logistics dashboard was also created and tested to allow the logistics team to efficiently validate data being captured across the military base. The validation was important as it allowed the driving team operating the vehicle to see the data being captured through the onboard monitor in real time. A handheld thermal imaging camera was also used. The LWIR cameras converted camera output data from pixel values to temperatures. Other subtasks included optimizing imaging hardware based on potential building materials to be encountered on military installations; finalizing the logistics plan for the imaging team, coordinating base access, finalizing paperwork for clearance and training Data Collection Technicians on using the onboard logistics dashboard.

4.1.6.2 Phase 2 – On-site scanning operations, data collection and preliminary data analysis

The contractor drove to Scott AFB and scanned over 250 buildings at the installation using the imaging vehicle, and captured data using the handheld camera for a subset of six of the buildings scanned by the imaging vehicle. The contractor set up comparative tests to determine the quality of data collected from the mobile imaging process relative to the data collected from the conventional thermal imaging method. For example, a data quality test was conducted to determine the difference between gathering the street-view of a building versus capturing all sides with a manual camera. The captured data were verified through manual curation, and the contractor worked with Scott AFB facilities managers to access GIS and energy information. The contractor customized an analysis pipeline for post estimation and converting raw images to temperature images and data processing. The data were processed to match images to both vehicle GPS data and GPS data gathered from the military installations. After this, the captured data were correlated to building information obtained from the installation. Further analysis was focused on building materials and correlating thermal inefficiencies to the areas imaged. The processing pipeline was configured to calculate energy scores for scanned buildings and determine the least efficient buildings. The results were published through an automated system that could be visualized using a front-end tool to manually verify building issues.

4.1.6.3 Phase 3 – down select and detailed analysis of 30 buildings

The contractor created a web-based Drive-by Visualization Application to identify buildings that required further analysis and also made the application available to the installation to allow them to downselect a subset of 30 buildings for detailed analysis. The Drive-by Visualization Application displayed the thermal imaging video, a map of the base, and a list of the buildings selected for further analysis. The user then selected or unselected a particular building for analysis. The gathered data from the handheld scanner were analyzed to provide a detailed comparative analysis.

4.1.7 Fundamental problem

Collecting useful building envelope energy efficiency data using traditional auditing methods is slow, costly, and difficult to scale. The demonstrated technology creates a new way to collect and analyze building envelope energy efficiency data, and augments (and in certain cases completely replaces) manual handheld audits of a building's envelope.

4.1.8 Demonstration question

Can mobile thermal imaging collect building envelope energy efficiency data faster and more cost effectively than traditional handheld thermography without compromising the quality of diagnostic information being acquired?

4.2 Baseline characterization

4.2.1 Reference conditions

The following data were collected for each military installation: building footprints (in the form of GIS polygons), parcel footprints (in the form of GIS polygons), address points, address metadata, energy consumption data (gas and electrical, only available for certain buildings) for multiple years for each metered building, building vintage, and building size.

In addition to infrared imagery, near infrared imagery, GPS and LIDAR data, other data collected by the imaging rig on scanning nights included: ambient temperature, ground temperature, sky temperature, and precipitation levels.

Scott AFB provided GIS data, however, energy data were not available for all buildings scanned at the installation.

4.2.2 Baseline collection period

The on-site scanning data for Scott AFB were collected over the period of 28 February to 1 March 2014. Data were collected on nights where the temperature and weather conditions were conducive to thermal imaging. Handheld thermography images were captured on the same nights.

4.2.3 Existing baseline data

Given the nature of the technology and this demonstration, there was no baseline data for comparison purposes.

4.2.4 Baseline estimation

The cost of conventional handheld infrared thermography was estimated based on the cost of equipment and the market rate of skilled labor to perform the analysis. Measurements of six selected buildings were taken with handheld infrared cameras to create a baseline to compare with the results from the vehicle-mounted rig.

4.3 Design and layout of system components

4.3.1 System design

The thermal imaging rig combines several commercial off-the-shelf sensors with custom electronics, software and environmental housing to record data samples:

- Trimble A3000 DR+GPS
- Velodyne HDL-32e 3D LIDAR
- (4) FLIR A65 Thermal imaging cameras
- (2) Allied Vision Technologies Manta G-283B Camera
- SICK LMS111-10100 2D LIDAR.

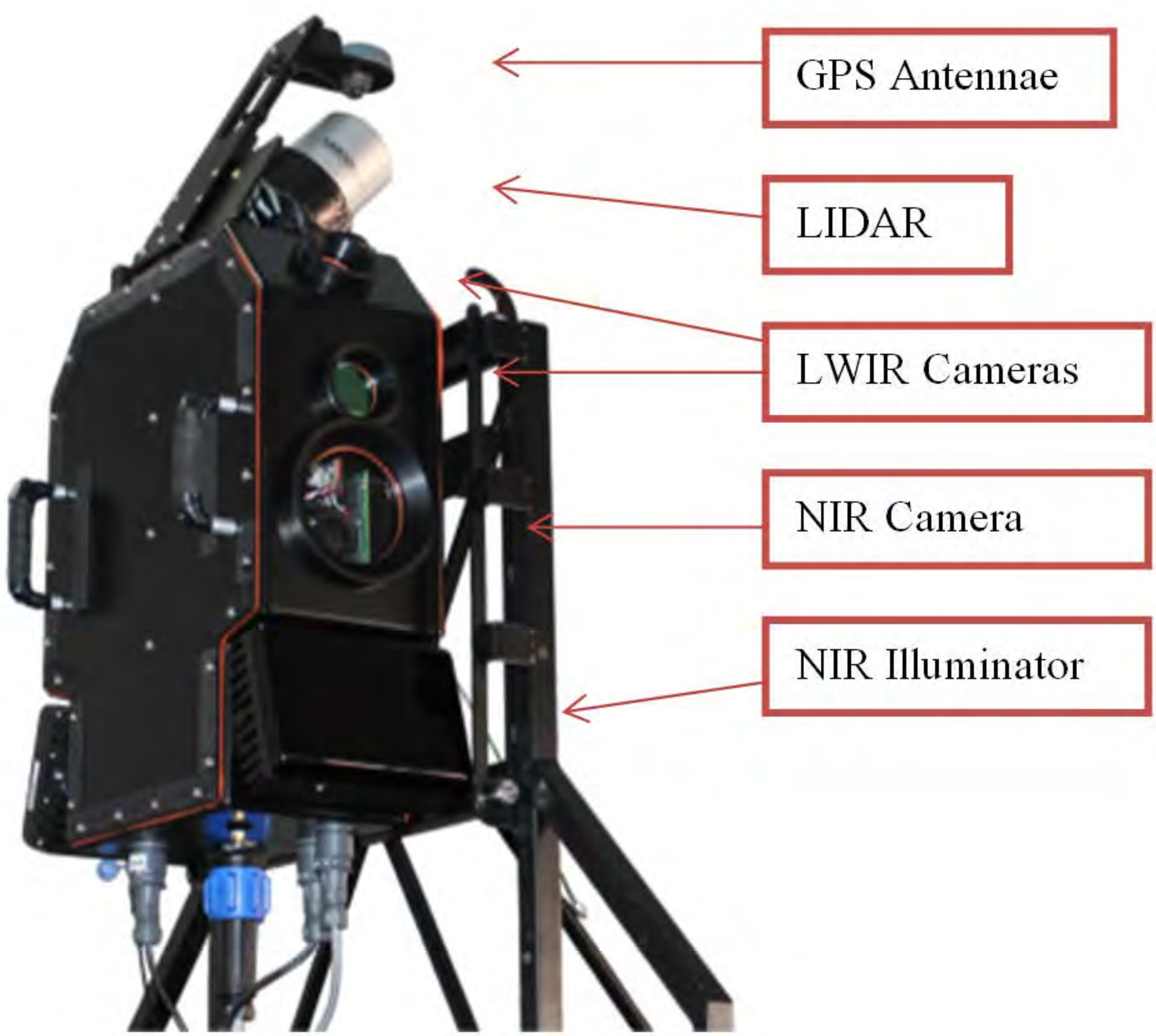
The Trimble GPS along with the front facing SICK LIDAR were used to continuously estimate the position of the car during the scanning process. The Velodyne LIDAR was used for 3-D reconstruction of buildings and other structures. The Manta cameras were used with the computer vision system to detect near infrared features. Thermal measurements were made with the FLIR long-wave infrared cameras. The data produced by these systems were recorded to a mirrored set of hard drives, and were post-processed using computer vision, machine learning, and thermal analysis algorithms to generate actionable envelope intelligence.

4.3.2 System layout

Figure 6 shows the multi-sensor imaging hardware. The GPS antenna maps the location of the car, the LIDAR creates a dense point cloud to determine the 3-D landscape, the long-wave infrared (LWIR) cameras measure heat, the near infrared (NIR) cameras are able to detect building features similar to what someone might see through a night vision camera, and the NIR illuminator acts as a floodlight for the NIR camera.

Figure 7 shows a schematic outline of the proprietary thermal imaging system. Figure 8 shows a snapshot of the user interface for the onboard data capture and diagnostic system interface that allows an imaging technician to validate the data as they are being collected.

Figure 6. Essess' multi-sensor imaging hardware.



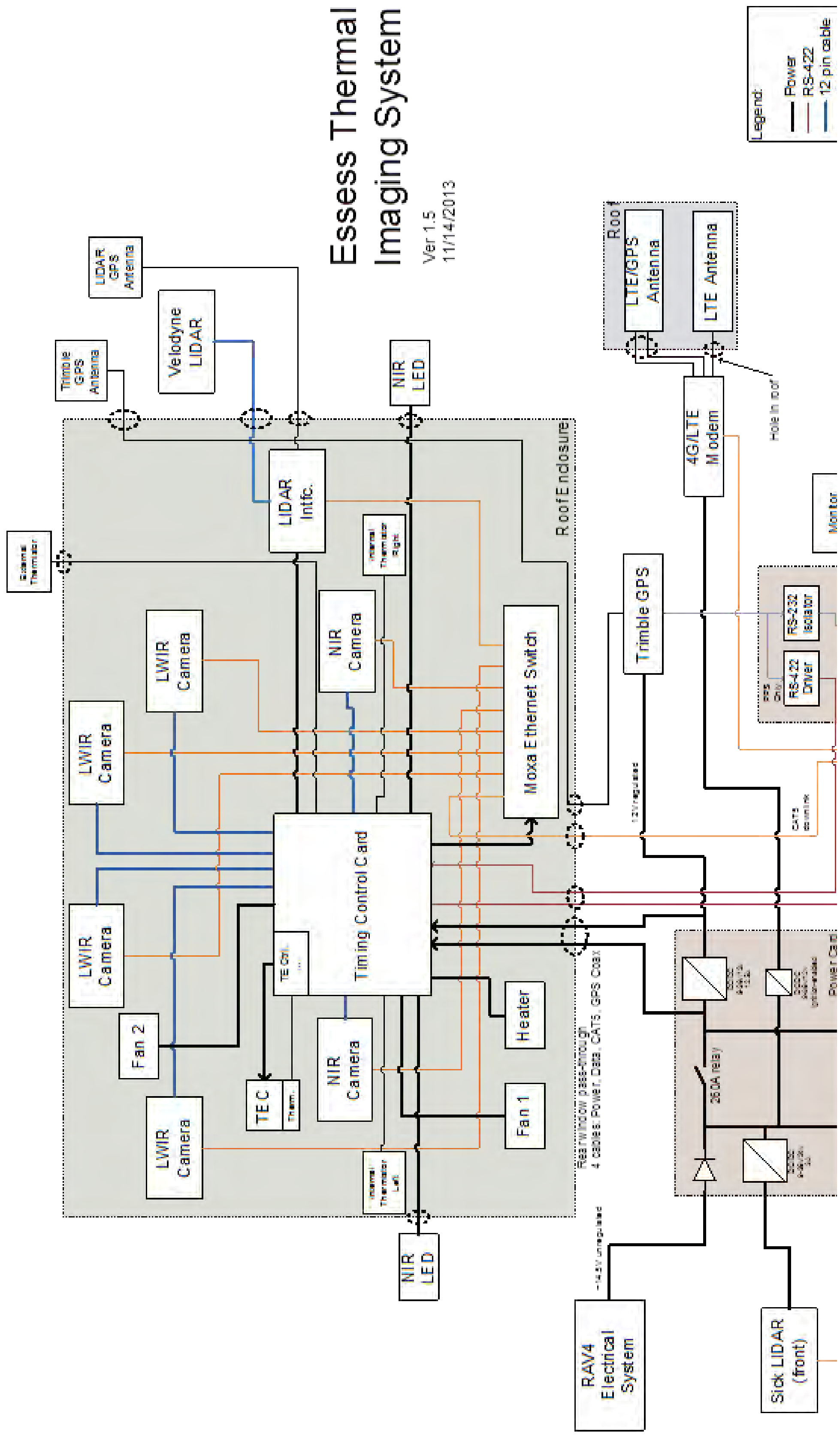


Figure 7. Schematic outline of the proprietary Essess Thermal Imaging System.

Figure 8. User interface for the onboard data capture and diagnostic system.

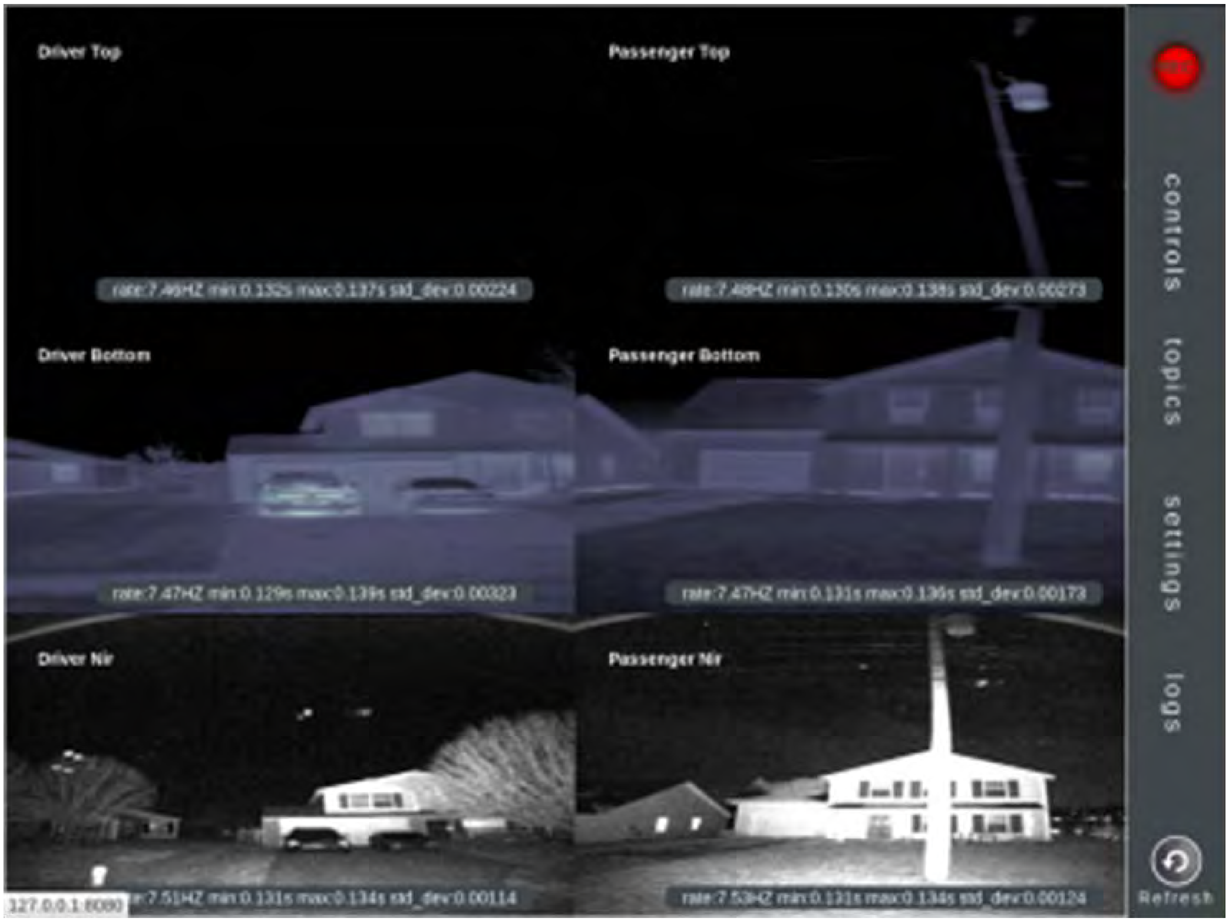
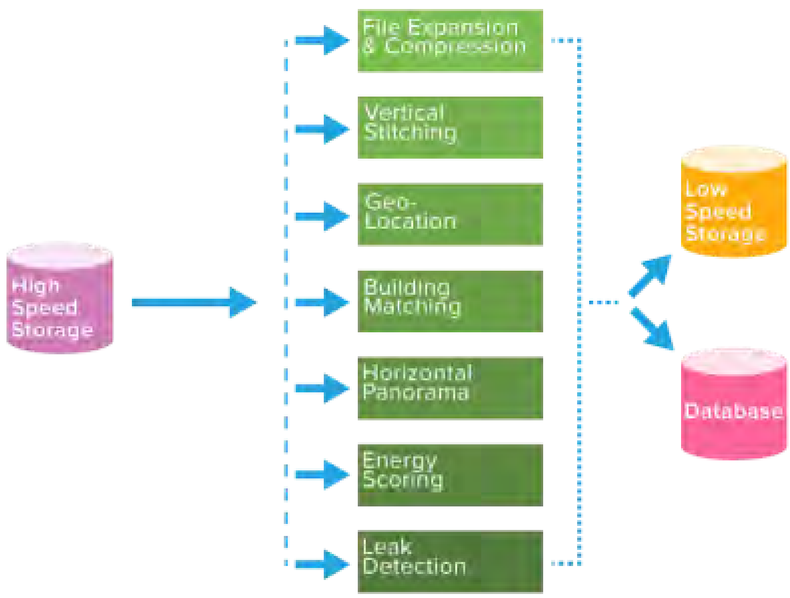


Figure 9 shows a very general overview of some of the key steps in the data processing pipeline, including:

- *High Speed Storage*. The imaging vehicle captures several terabytes of data per night, which are stored in the Customized Vehicle Data Storage System.
- *File Expansion and Compression*. The compressed data are extracted from the hard drives to begin processing and analysis.
- *Vertical Stitching*. The vehicle is equipped with two LWIR cameras mounted one above the other on each side of the imaging device and each camera captures a portion of the vertical scene as the vehicle passes by. To get a robust, vertical image of the scene, data streams from the two cameras are stitched together using proprietary algorithms.
- *Geo-location*. All of the data from the GPS units are analyzed and then combined with LIDAR information to adjust for any external noise or loss of satellite signal.

- *Building Matching*. Once the GPS data are processed and analyzed, they are matched up with the relevant thermal images for each building imaged.
- *Horizontal Panorama*. As the data are captured frame by frame, there may be tens or hundreds of individual images, each showing a small part of the entire scene. To get a seamless panorama of an entire building, the frames must be stitched together.

Figure 9. General overview of the Essess data processing pipeline.



- *Energy Scoring*. Once the images are extracted, vertically stitched, correlated with the relevant address, and horizontally grouped, they are analyzed to convert the thermal reading into an energy score. This energy score is relevant to each data set and allows for one building to be compared to a different building within the same data set.
- *Leak Detection*. The images are also analyzed for potential building envelope leaks.
- *Low Speed Storage*. All of the raw data are then placed in low speed storage.
- *Database*. The analyzed and processed data are stored in a database. Customers can then access this data using web applications layered on top of the database.

4.3.3 Heat flux calculation methodology

4.3.3.1 Calculating heat flux

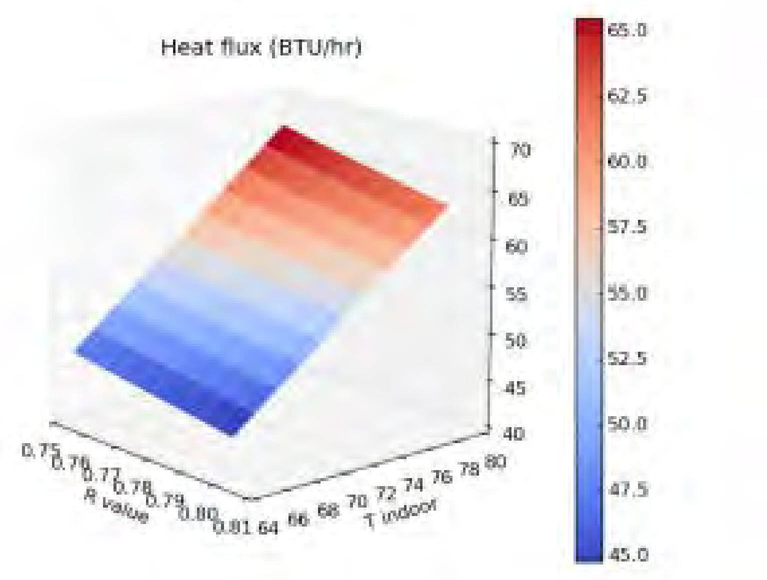
Heating energy losses (Figure 10) due to conduction through walls, roofs, windows, doors, and soffits were calculated by the equation (Schiler 2005):

$$Q_{h,d} = A \cdot U \cdot (T_{in} - T_{out}) \tag{4-1}$$

where:

$Q_{h,d}$	=	Total hourly rate of heat loss through surface in Btu/hr
U	=	Overall heat transfer coefficient of surface in Btu/hr-ft^2-°F
A	=	Net area of surface in ft^2
T_{in}	=	Inside temperature in °F
T_{out}	=	Outside temperature in °F.

Figure 10. Heat flux (Btu/hr).



This analysis focused only on heat loss and assumed an indoor average thermostat (T_{in}) setting of 69 °F ± 4 °F (65 °F to 73 °F). This is slightly lower than the actual most likely thermostat setting to account for internal heat gain due to lighting, electronics, and machinery.

The hourly outdoor temperature (T_{out}) was obtained from the National Climate Data Center (NCDC) Quality Controlled Local Climatological Database (QCLCD).

The area of the surface was determined based on the relative size of polygons drawn on the building compared to door polygons (or synthetic door polygons when doors are not present). Doors were assumed to have an area of 20 sq ft, and were drawn individually so as not to conflate double doors with single doors.

The U value of elements of the building envelope were estimated based on their surface material, brightness, and the relationship between the indoor temperature, the surface temperature, and the outside air temperature. Specifically, calculations were done to determine the heat loss (radiative + conductive to the outdoor ambient air) of a material to the outside air assuming steady state for that heat flux and the estimated indoor temperature, then to determine the R value for that portion of the building surface. The approach taken is described in detail in the subsequent section.

The sensible heat loss from infiltration can be calculated as (Bhatia 2014):

$$Q_{h,i} = V_{cfm} \cdot \rho_{air} \cdot C_p \cdot (T_{in} - T_{out}) \cdot 60 \quad (4\text{-}2)$$

where:

$Q_{h,i}$ = sensible heating load from infiltration in Btu/hr
V_{cfm} = volumetric air flow rate in cubic feet per minute (CFM)
ρ_{air} = the density of the air in lb/ft^3
C_p = specific heat capacity of air at constant pressure in Btu/lb°F.

The indoor and outdoor temperatures are the same as above. The density of air (ρ_{air}) is, on average, 0.074887 lb/ft^3. The specific heat capacity of air (C_p) is assumed to be 0.2403 Btu per (°F) (lbs).

The volumetric air flow rate per linear foot of door and window frame cracks was assumed to be 0.52 CFM on average for a pressure differential of 75 Pascals, with a standard deviation of 0.4 CFM and a minimum of 0.01 (Weidt and Weidt 1979; Shaw 1980; Gowri, Winiarski, and Jarnagin 2009; SAG 2014). At an average interior to exterior pressure differential of 10 Pascals, this translates into a mean CFM of 0.14, based on the functional relationship between air flow and pressure (Weidt and Weidt 1979):

$$Q = C(\Delta P)^{0.65} \quad (4\text{-}3)$$

The volumetric air flow rate of any given linear foot of leaks was estimated based on its relative emissivity compared to the mean of all observed windows and doors with the assumption that the distribution of leaks at both Scott AFB and Camp Lejeune roughly matches that found in the literature

(Weidt and Weidt 1979; Shaw 1980; Gowri, Winiarski, and Jarnagin 2009). Windows and doorframes were tagged separately from the window glass or door material, and the linear feet of cracks were estimated based on the dimensions of the frame relative to the door reference described previously. The mean emissive cracks were assigned an estimated value of 0.14 CFM; the 95th percentile of emissive cracks was assigned an estimated value of 0.36 CFM.

Total heating losses can be calculated as the sum of conductive and convective heating losses, adjusted based on the efficiency of the heating equipment. Assuming a natural gas space heating system with an average fuel use efficiency (f_{afue}) of 70% per the Illinois Technical Reference User Manual (TRM) default assumption for existing systems in commercial buildings (SAG 2014), total heating losses (in therms per hour) were calculated as:

$$H_{therms} = \frac{Q_{h,d}+Q_{h,i}}{f_{afue}} \cdot \frac{1}{99{,}976} \tag{4-4}$$

Total cooling losses were estimated as the sum of conductive and convective cooling losses, with a typical Seasonal Energy Efficiency Ratio (SEER) of 10 Btu/watt-hour (f_{seer}) per the typical value of existing equipment in the TRM (SAG 2014):

$$C_{kwh} = \frac{Q_{c,d}+Q_{c,i}}{f_{seer}} \cdot \frac{1}{3{,}412} \tag{4-5}$$

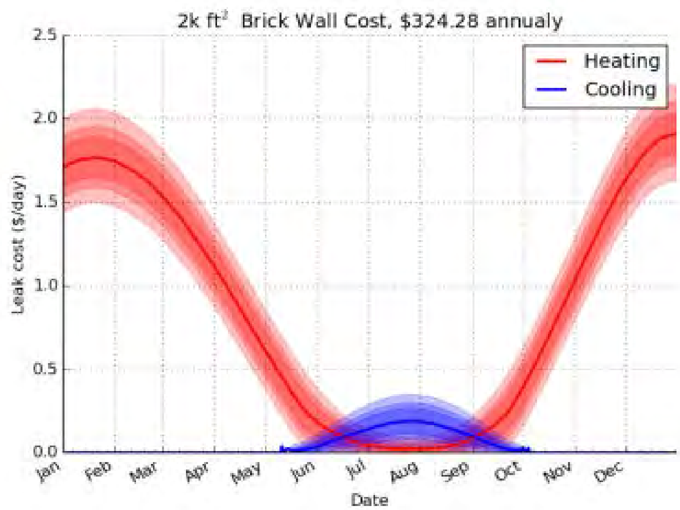
Figure 11 shows an example of the results of this approach for a characteristic brick wall. For the time being, energy losses due to latent heat were excluded from this analysis. The analysis assumed a cost per kWh of $0.056 and cost per therm of $0.59.

4.3.3.2 Inferring R-values

R-values were inferred by using a conservation of energy principle to assume that all energy leaving the surface of the material is matched by the energy flowing through the material. If the system is at steady state, the heat flowing through the material is equal to the heat leaving the material surface:

$$q_{through} = q_{exit} \tag{4-6}$$

Figure 11. Brick wall cost.



Where $q_{through}$ is the heat flux through the material (inside the building to outside) and q_{exit} is the heat flux leaving the material and escaping into the atmosphere. The leaving heat flux can be split into two components: radiation (beaming photons) and conduction (warming up the film of outside air that touches the material).

$$q_{exit} = q_{rad} + q_{cond} \tag{4-7}$$

The radiation heat flux is:

$$q_{rad} = \epsilon\sigma A\left(T_{surf}^4 - T_{out}^4\right) \tag{4-8}$$

where epsilon (ϵ) is the emissivity of the gray body (a description of how shiny the material is), sigma (σ) is the Stefan-Boltzmann constant, area (A) is the material surface area, surface temp (T_{surf}) is the material's external surface temperature, and outdoor temp (T_{out}) is the ambient outdoor air temperature. Here it was assumed that most objects that are radiating back toward the building material were at approximately the ambient air temperature.

The exiting conductive heat flow is:

$$q_{cond} = hA\left(T_{surf} - T_{out}\right) \tag{4-9}$$

where h is the heat transfer coefficient of air.

This exiting heat flux is equal to the heat flux through the material:

$$q_{through} = \frac{(T_{in} - T_{out})A}{R} \tag{4-10}$$

where R is the thermal resistance and indoor temp is the indoor air temperature.

Solving for the thermal resistance:

$$\hat{R} = \frac{A(T_{in} - T_{out})}{q_{through}} = \frac{A(T_{in} - T_{out})}{q_{exit}} \tag{4-11}$$

As mentioned previously, this method only produces an unbiased estimate of R-values in cases where the system is at a steady state. In practice, this will often not be the case due to residual solar heating of material surfaces and uncertainties in precision of measured surface temperatures and outdoor air temperatures. Failing to account for these will tend to result in a systemic underestimate of R-values, and concomitant overestimate of remediation potentials.

To effectively control for these uncertainties, the resulting R value estimates were normalized based on a prior distribution of assumed R-values in the literature (archtoolbox 2014, ORNL 2004) for each component (Table 3).

Table 3. Current component R-values and new component R-values

	Current Component R-Values				New Component R-Values			
Component Name	Min	Max	Mean	St Dev	Min	Max	Mean	St Dev
Window – Glass	0.99	2.99	1.69	0.25	0.99	2.99	1.69	0.25
Door – Wood	1.85	3.7	2.17	0.5	1.85	3.7	2.17	0.5
Door – Metal	6	15	10	2.5	6	15	10	2.5
Door – Glass	1.8	5	2.5	0.5	1.8	5	2.5	0.5
Soffit	8	16	12	3	8	18	14	3
Exposed Foundation	6	14	10	2	6	14	10	2
Wall – Brick	8	16	12	3	8	18	14	3
Wall – Stone	6	12	8	2	6	14	10	2
Wall – Siding	6	12	8	2	6	14	10	2
Wall – Concrete	6	12	8	2	6	14	10	2
Roof	10	20	14	3	10	20	15	2.5
Wall – Thermal Bridge	4	12	8	2	8	18	14	3

Specifically, it was assumed that individual identified components on the installation map to a distribution of current component R-values, such that the 10th percentile of brick walls on the installation, would fit the 10th percentile of the normal distribution of current component brick wall R-values in the table.

This approach was conducted separately for areas with and without significant sunlight exposure on the evening of 28 February 2014 (e.g., south and southwest-facing surfaces between 120 and 300 degrees) (Suncalc 2014). It was expected that this should have mitigated bias due to residual solar heating, as all surfaces observed around the same time with the same orientation should have had similar biases. The relatively early cessation of direct sunlight also helped, as sunset occurred at 15:52. Figure 12 shows the angle and height of the sun relative to the horizon on February 28th for the Scott AFB area.

An additional analysis was done to measure the effect of the imaging time on the surface temperature of buildings. Figure 13 shows the results for south-facing brick walls, which broadly indicate most other components observed. Given that the effect of time of observation on resulting surface temperatures is roughly equal in magnitude to the variation in surface temperature among buildings sampled, an explicit time-of-observation correction was warranted, using a simple ordinary least squares detrending approach on each combination of building component and orientation to normalize for time of observation.

Additional factors that may introduce bias into the estimate included:

- *Unknown Material Types*. Currently, the process relies on human curators to tag the building component with the correct material type. If this type is wrong, then the model is no longer as accurate. This could be addressed by additional validation of component material types against aerial imaging, as well as review by base staff.
- *Imprecise Local Temperature*. Currently, ambient outdoor air temperatures are read from weather station logs, which are precise only to a single degree Fahrenheit. This introduces some error in the heat flow model, which is sensitive to temperature values. This could be addressed by incorporating data from the vehicle-mounted temperature sensor, or by readings from an on-base weather station.

Figure 12. Angle and height of the Sun relative to the horizon on February 28 2014 for Scott AFB.

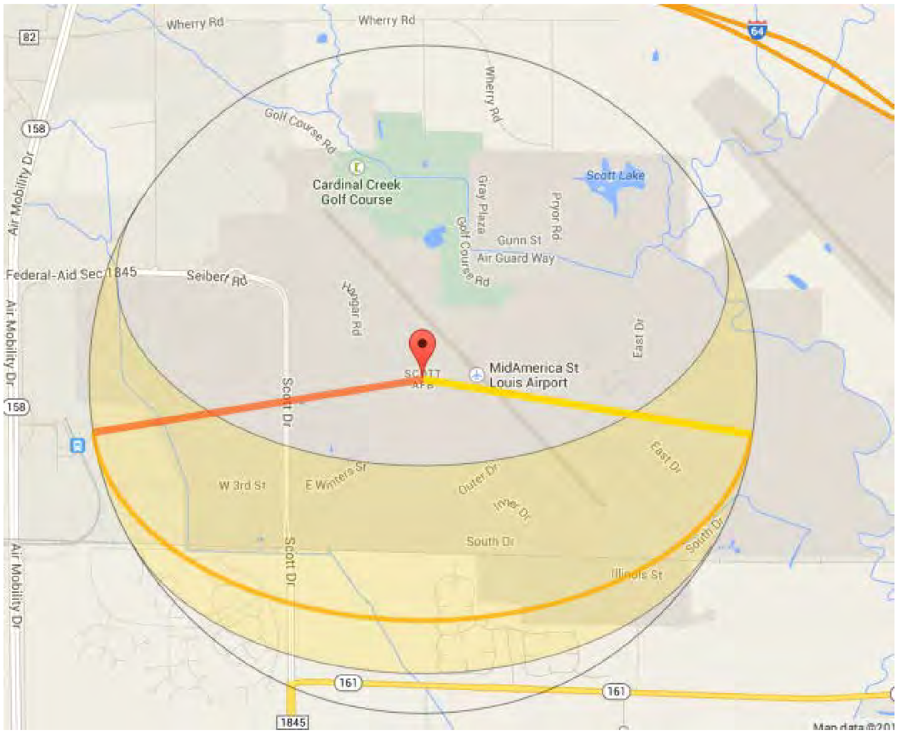
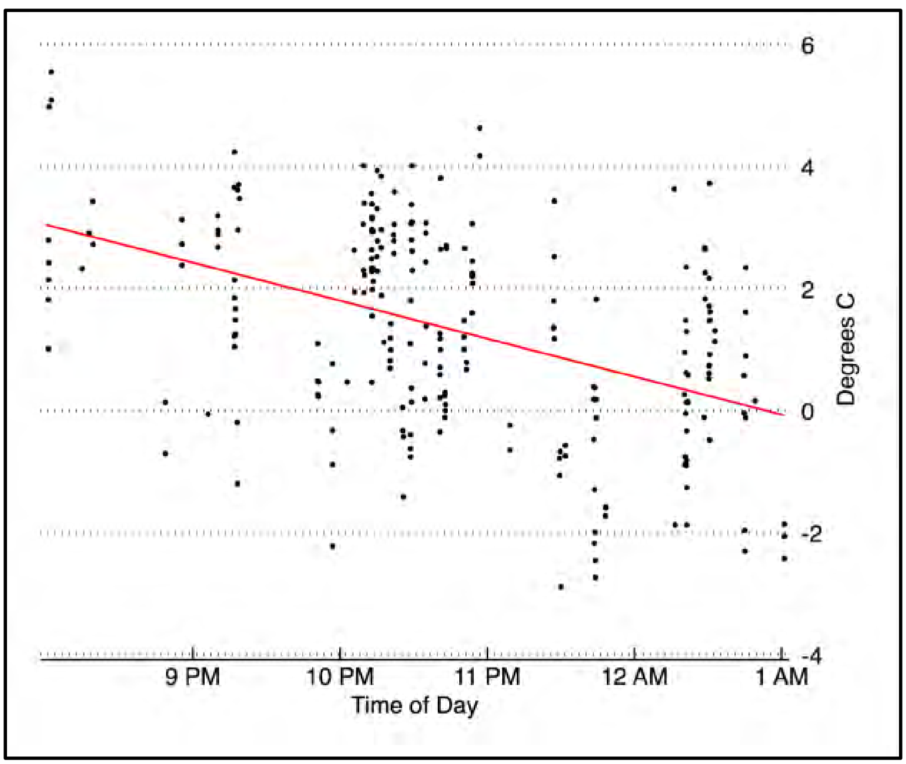


Figure 13. Building surface temperature values over time.

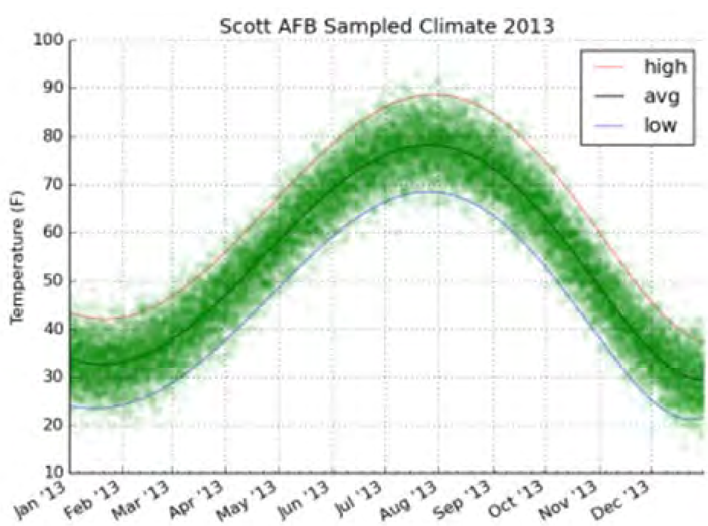


- *Unknown Indoor Temperature*. Because it is impossible to read indoor temperature through the building surface, it must be estimated. In this work, indoor temperature was estimated using common temperature values that most people find comfortable, such as 65-73 °F in the winter and 70-78 °F in the summer. This could be addressed by receiving more information from facility managers regarding indoor summer and winter thermostat setpoints.
- *Uncertain Space Heating and Cooling Efficiencies*. There is a range of potential efficiencies of 60–95% for space heating and SEER ratings of 8 to 18. Lack of detailed information about building-specific heating, ventilating, and air-conditioning equipment prevented these estimates from being further refined. Currently, mean estimates of 70% Annual Fuel Utilization Efficiency (AFUE) were used. A cooling system SEER of 10 was used.

4.3.3.3 Temperature data analysis

To determine the potential savings of remediation measures over the cooling and heating seasons, assumed indoor temperatures were compared to typical outdoor temperatures based on average hourly data over the past 5 years from a National Weather Service weather station located in Belleville, IL. This was obtained via the NCDC's QCLCD (NCDC 2014). Missing values were in-filled by adding an interpolated anomaly field to the average climatology of the missing hourly reading. Figure 14 shows the typical climate for Scott AFB in the year 2013.

Figure 14. Scott AFB sample climate 2013.



4.3.4 System integration

Although both handheld thermography and mobile thermal imaging use LWIR to determine energy loss, the imaging rig supplemented LWIR with NIR, LIDAR, GPS, and other sensors to gather better building diagnostic data. As a result, the final analysis can fully replace traditional handheld methods for gathering external building envelope data. This mobile thermal imaging technology allows the military to conduct baseline building envelope energy efficiency audits for hundreds of buildings in a matter of hours instead of months.

4.4 Operational testing

4.4.1 Operational testing of cost and performance

Data collection involved having an imaging rig drive to a given location and scan the area based on pre-defined, routing tracks. The imaging team waited until sunset to set up the system and then to begin imaging. This mitigated the effects of solar radiation and allowed the team to capture data at a period with the largest temperature difference (middle of the night). To ensure that the best data were captured, the contractor avoided imaging during any kind of precipitation events. Costs captured for driving the imaging rig included technician labor costs, cost of fuel for the imaging rig, and operating and maintenance costs.

4.4.1.1 Modeling and simulation

All imaging data were logged onto the onboard data capture and diagnostics system. The onboard imaging technician was able to view the data as they were recorded to spot any problems in the data quality. Once the data were sent to Essess headquarters, they were processed and used for algorithmic testing. The algorithmic testing provided information on the cost, time, and image quality for mobile imaging versus traditional handheld thermography methods.

4.4.1.2 Timeline

Operational testing plan (Table 4) commenced in February 2014.

Table 4. Essess schedule of work.

Task		2013	2014												2015	
		12	1	2	3	4	5	6	7	8	9	10	11	12	1	2
1	Prepare plan for scanning															
2	Scan buildings															
3	Process and Analyze Data															

4.4.1.3 Decommissioning

There was no need for decommissioning since this project involves a contracted service and a mobile scanning system.

4.4.2 Equipment calibration and data quality issues

The field engineer used an asymmetric circle calibration grid to optically calibrate the long-wave infrared cameras according to industry best practices (Figure 15) The thermal calibration was conducted using a black body radiation source at Essess headquarters.

The LIDAR was calibrated by its manufacturer, Velodyne, and qualitatively verified by the contractor. Sampling frequency was optimized based on the hardware limitations of the sensors and storage systems. The contracted imaging team allocated a specific imaging technician to resample a subset of the data to ensure that they were internally-consistent.

Figure 15. LWIR camera calibration device.

4.5 Sampling protocol

4.5.1 Data description

Terabytes of thermal imaging, LIDAR and GPS data were collected at Scott AFB. For a subset of six of the buildings scanned by the drive-by method, data were collected using a handheld thermal camera to do a comparative analysis between handheld thermography and drive-by KSR LWIR scanning to determine the efficiency (amount of time taken to scan) and effectiveness (ability to identify energy leaks) of each method.

4.5.2 Data storage and backup

Data were written into 2 GB files to a mirrored disk array and checksums were generated and stored as metadata to ensure long term data integrity. The data were physically uploaded to a secure, private cloud system and physical hard drives were stored as back-ups at Essess' headquarters in Boston, MA.

4.5.3 Data collection diagram

The data collection approach was described in detail in Section 4.3 (Design and Layout of System Components).

4.5.4 Post-processing statistical analysis

Several layers of testing and data quality measurement were used at each stage of processing, from initial data acquisition to final presentation of energy analysis results. When the data capture system started, it performed sensor integrity checks, ensuring that each sensor was communicating with the main computer and sending valid data. Throughout recording, the system continued to monitor data quality, such as valid temperature ranges, image information content, GPS location, and LIDAR distance measurements. The system also monitored sensor connectivity, and raised errors if a sensor had stopped communicating. Any error or warning messages were immediately logged to a system diagnostics log and also displayed to the onboard display for the driver and navigator. At any time, a technician could log into the mobile system remotely and securely, view the images and other sensor data, and update the recording system software.

When the hard drives were imported into the secure data storage system, the import agent program ran a more rigorous data quality filter. This filter checked for data file integrity and file size, image size and information content, the frequency of each sensor message, the presence of each sensor data stream, and additional in-depth screens for GPS location noise, image pixel values, LIDAR distances and point cloud sizes with scene distances, and thermistor readings. It also checked the data feed of sensor chamber operating conditions to make sure that the sensors were kept within specified operating temperatures. All sensor data passing these quality control checks were marked and queued for further analysis. There were few instances of unusable data caused by sudden onsets of precipitation while the team was still imaging. These data were limited and did not affect the overall analysis since the team paused the imaging until there was no precipitation.

During data processing and energy analysis, each stage of the processing pipeline passed its intermediate results through quality filters that checked for data validity, such as scene temperature readings, building metadata, GPS location consistency, raw energy flow estimates, and energy scores.

In addition to these data checks, the software behavior was tested several times a day in an automated testing environment. Each piece of processing code was built with unit tests, and integration tests checked the interaction of various software modules. The entire software infrastructure was built with continuous integration and continuous deployment, allowing for fast feedback and agile development.

Above the normal quality control process for this study, the contractor performed outlier detection in utility consumption data to detect outliers of energy usage per square foot of building area grouped by building type. Specifically, the contractor fit elliptic envelopes of data distributions using Mahalanobis distance. The Mahalanobis distance is a way of determining the “similarity” of a set of values from an unknown sample to a set of values measured from a collection of “known” samples. It measures the separation of two groups of objects. For more information please see: http://www.encyclopediaofmath.org/index.php/Mahalanobis_distance.

4.6 Results for Scott Air Force Base, IL

4.7 Sampling results for Scott Air Force Base, IL

The kinetic super-resolution long-wave infrared integrated scanning team identified 3,263 distinct feature components on 146 different buildings on Scott Air Force Base out of a total of 328 buildings and other objects surveyed. These features were categorized by type (e.g., brick wall, roof, window glass, window frame) and surface temperature. Heat losses were calculated based on the temperatures of the features, the times of observation, the orientations of the features, and the outdoor air temperature as described in Section 4.2 (Baseline Characterization).

This analysis of Scott AFB identified $304,393 in potential annual building envelope-related electricity and natural gas savings across all buildings on the base for remediation measures that have a payback period of 15 years or less (see Section 4.2 for detailed calculation methodology). These savings would require approximately $2,211,500 in capital expenditures for remediation. The recommended measures include retrofitting of walls, soffits, and roof insulation and sealing leaks around windows and doorframes. Total savings from these remediation measures could save Scott AFB approximately $4,385,376 over the lifetime of the projects (15 years on average), and the measures would pay for themselves after 7.3 years. This is based on the assumption (based on field tests while the technology was being developed in the laboratory) that envelope-related issues and potential savings observed from the street were representative of the sides not visible from the street *on a per-building basis*, something generally true when examining buildings where all four sides are available. Note that, for the majority of buildings, at least 33% of the surface area of the building was scanned due to the fact that the imaging system typically views at least two sides of a building.

For areas visible from the street, this analysis showed $113,264 in potential annual building envelope-related savings across all building components imaged with a payback period of 15 years or less. These savings would cost approximately $824,985 in capital expenditures for remediation and a payback period of 7.3 years.

Figures 16 to 18 show spatial results of the analysis of conductive* leaks, convective† leaks, and all remediation measures. The map shown in Figure 16 represents the average dollar loss per square foot of floor area from conductive leaks, e.g., leaks of energy through walls, roofs, and other surfaces due to poor insulation. Buildings highlighted in red are the most emissive, with the highest annual conductive heating and cooling losses (dollars per square foot of floor area).

Figure 17 shows the average dollar loss per square foot of floor area from convective leaks, e.g., leaks of energy through infiltration via cracks and gaps in door and window frames. Buildings highlighted in red are the most emissive, with the highest annual convective heating and cooling losses per square foot of floor area.

The below Payback Period for Envelope Measures map (Figure 18) shows the combined cost effectiveness of the remediation of conductive and convective leaks expressed as a payback period (in years). Buildings in blue have an attractive payback period, while buildings in red have a less attractive payback period.

4.7.1 Recommended envelope ECMs

A number of energy conservation measures (ECMs) are recommended for specific buildings on each base. These were determined by a combination of thermal imaging, energy consumption analysis and disaggregation, and building characteristics.

When determining the optimal envelope ECMs to recommend for a given building, the relative cost effectiveness of each ECM is compared to other available options based on the specific heat loss characteristics of the building in question. The method for calculating potential savings through envelope ECMs is characterized by a comparison of the heat flow across every hour of the year (for both cooling and heating) for an estimated current R value and a new post-remediation R value, incorporating hourly outdoor temperatures based on weather data.

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* Conductive heat loss involves heat being lost through the building's walls, thermal bridges or roof. If one surface of a wall is at a higher temperature, then the heat will be transferred through the material to the other surface which is at a lower temperature. This type of heat loss typically depends on three factors: the size of the building, local weather conditions, and the building envelope's capacity to resist heat loss.

† Convective leaks or convective heat loss refers to heat being lost through air leaks. For heating, it is the process by which heat is lost by warm air leaking to the outside when a window or door is opened or cold air leaking into the building through cracks or openings in walls, windows, or doors.

Figure 16. Average conductive heat loss for Scott AFB.

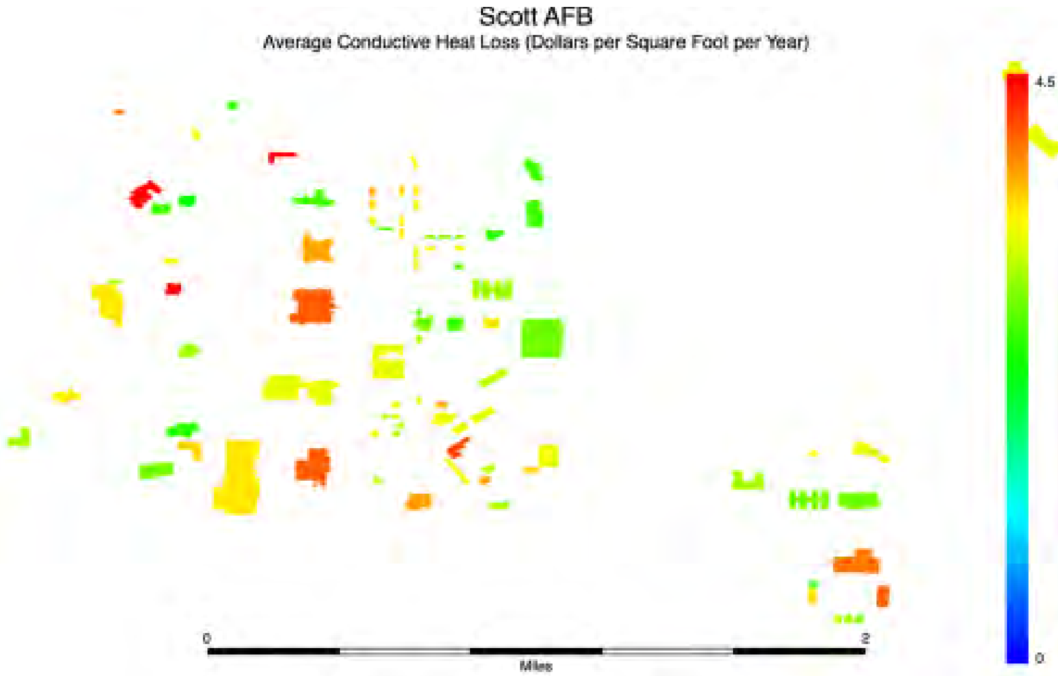


Figure 17. Average convective heat loss map for Scott AFB.

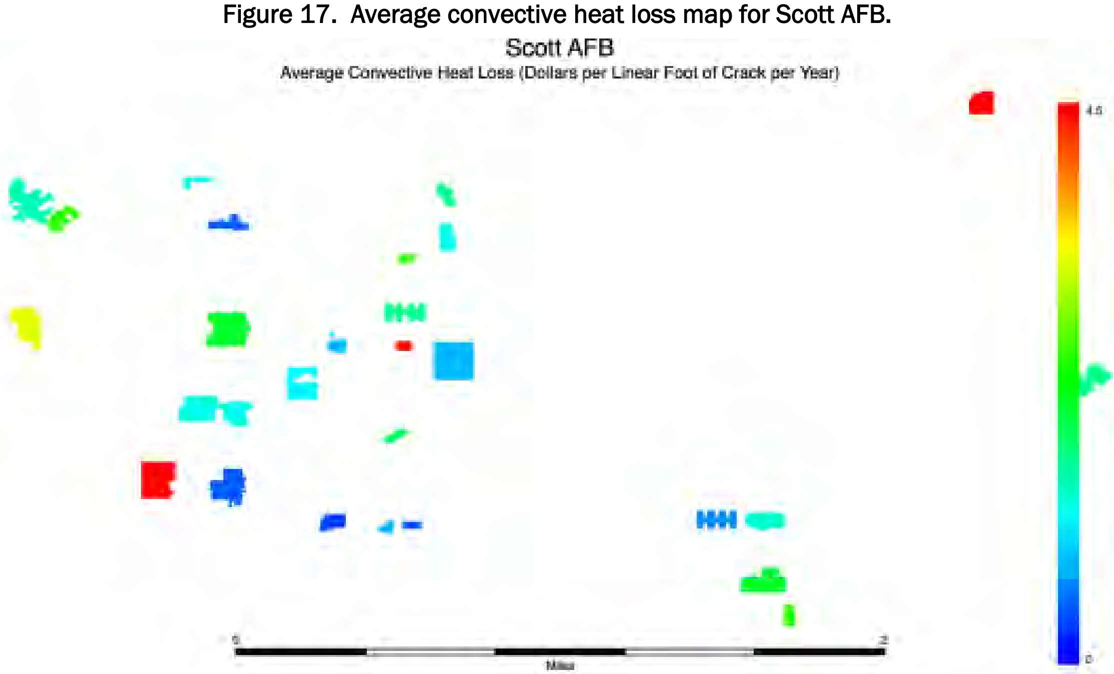
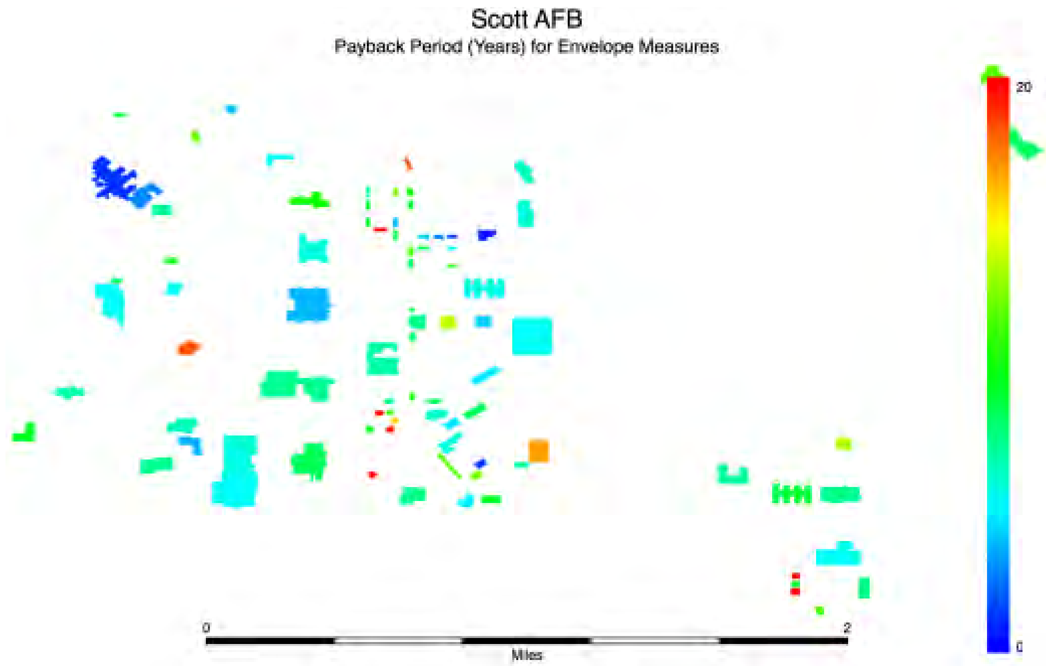


Figure 18. Payback period for envelope measures for Scott AFB.



Air sealing-related ECMs involve a similar approach by comparing the difference between estimated current infiltration rates per linear foot of crack and post-remediation infiltration rates. Section 4.2 (Baseline Characterization) describes the technical details of how these are calculated.

The specific envelope ECMs examined include:

- *Improve Wall Insulation*. This can encompass either patching up discrete insulation holes, or improving the overall insulation of a wall through the addition of blown or sheet insulation.
- *Improve Roof Insulation*. This can encompass either patching up discrete insulation holes, or improving the overall insulation of a roof/ceiling through the addition of blown or sheet insulation.
- *Improve Soffit Insulation*. Soffits are the junction between walls and roofs and are often poorly insulated. In many cases they can be accessed and have their insulation improved.
- *Improve Exposed Basement Wall Insulation*. When buildings have part of their basement wall exposed, they can often benefit from installing insulation on the portion exposed to the air.
- *Seal Window Frame Leaks*. This involves using caulk or weatherstripping to seal cracks in window frames that are letting air in or out of the building.

- *Seal Door Frame Leaks*. This also involves using weather-stripping (and in some cases caulk) to reduce the size of gaps around doorframes while not hindering the operation of the door.

Window and door replacement are not recommended because they are generally not cost effective, especially in military facilities, where security requirements can increase the cost of window and door installations.

5 Performance Assessment

5.1 Relative cost effectiveness of handheld and mobile imaging methods

5.1.1 Handheld method

- Each building takes about 25 minutes of imaging work; necessary to overlap building components in each frame.
- Handheld unit is a FLIR i7 (The FLIR i-Series cameras are handheld thermal cameras specially designed for building diagnostics and commonly used in residential and commercial thermal audits).
- 140 x 140 pixels.
- 29 x 29 degree Field of View (FOV).
- Spotmeter, area with max/min. temperature, isotherm above/below.
- Scanning Cost: $920,000 for Scott AFB. Based on the amount of building space imaged, the estimated cost is ~ $1,000 per 5,000 sq ft of floor space.

5.1.2 KSR LWIR method

- Each building takes about 30 seconds to scan
- Mounted in integrated system camera
- 640 x 512 pixels
- 45 x 37 degree FOV
- Temperature calculated per feature
- Material emissivity obtained by computer vision
- Scanning Cost: Set cost at $200,000 per installation, regardless of square footage

The KSR LWIR approach provides a number of significant advantages over conventional handheld infrared thermography, both in terms of the speed and cost of imaging and the quality and utility of the images and analysis.

Handheld radiometric imaging instruments are standard equipment for energy efficiency measurements of building envelopes. The use cases for these imagers are low throughput, non-quantitative work. Data are stored on a low speed secure digital (SD) card. Image contrast is tuned for visual use. The center point of reported temperatures is what is outputted to the user. Resolution typically ranges from 80 x 80 pixels to 150 x 150 pixels. The FOV is 30 x 30 degrees.

The kinetic super-resolution long-wave infrared integrated scanning system uses multiple radiometric thermal cameras. These devices are designed for high-throughput analytical and computer vision work. The devices are configurable through computer control and automation. Data flows from devices over a high speed local network to high speed redundant storage. Raw digital number information is stored for each image frame. Resolution per camera is 640 x 512 pixels. The FOV per camera is 37 x 45 degrees while the total field of view is 37 x 80 degrees.

Images can be acquired at a much faster rate using the Essess sensor system. There is continuous image acquisition without the need to frame the building since each frame contains overlapping information. Further, the raw information allows temperature conversions to be done per individual region in the frames versus just one temperature point in the handheld instrument. The Essess system also provides near infrared images associated with each long-wave infrared image. These provide the ability to pick out features and textures that may not be easily visible in the long-wave infrared image, as the near infrared image is similar to a conventional photograph (Figure 19).

5.1.3 Example performance in Scott AFB Bldg 8 (PAX Terminal)

Handheld thermographic data acquisition of Bldg 8 was collected within minutes of capturing thermographic data for the same building using the KSR LWIR scanning system. Handheld data were collected on foot. Each frame was acquired by walking until the desired portion of the facade was in view. The image was acquired and stored to the SD card. The total time exceeded 30 minutes. Data capture using the vehicle scanning system took only about 30 seconds because, except for the driver operating the vehicle, no manual interactions were required (Figure 20).

Due to the nature of how the data are stored in handheld systems, the raw data are not stored along with the colored and contrasted temperature image. This means that it is more difficult to accurately determine the temperature fluctuation from one part of a building to the next. Without the temperature data, one solely depends on the color of the image.

Figure 19. Handheld thermographic image (left) versus the KSR LWIR thermographic image (right) for Scott Air Force Base

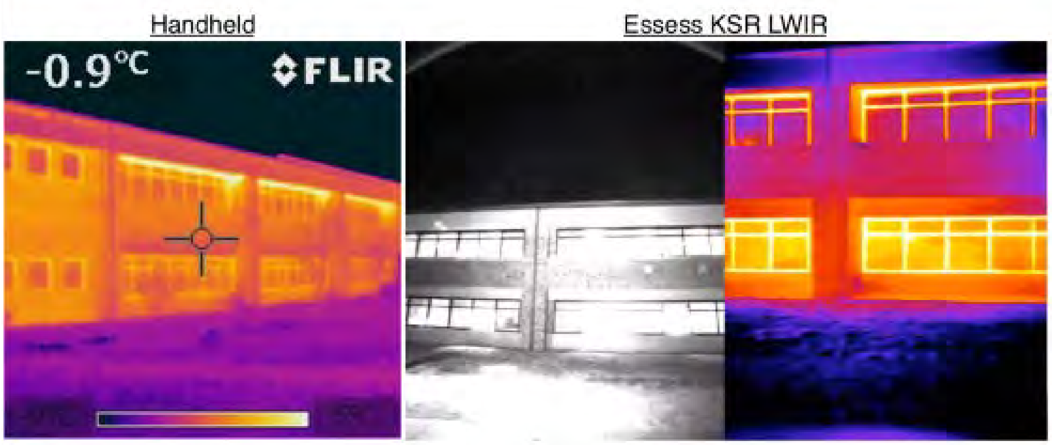
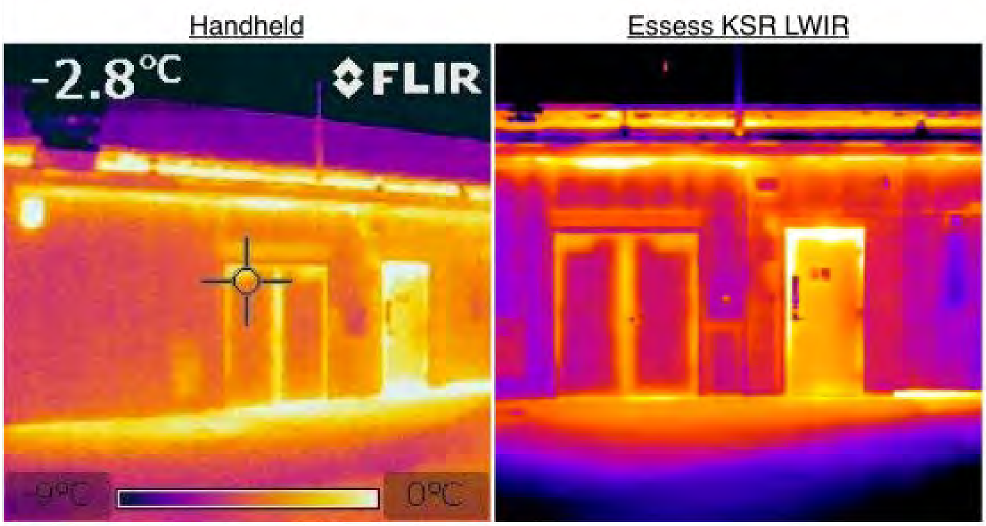


Figure 20. Handheld thermographic image versus the KSR LWIR thermographic image for Bldg 8, Scott AFB.



Furthermore, the emissivity of the material type must be set before the image can be acquired. Imaging multiple materials makes thermal calculations inaccurate. This makes it nearly impossible to use a handheld camera's data to accurately assess building facade temperature. Capturing continuous, video format handheld data acquisition is hampered by multiple factors. Framing shots is the limiting factor in throughput of imaging the entire building. The secondary factor in limiting throughput is the storage media (20 MB/second), which is approximately 12-20 times slower than Essess' data collection system storage rate.

5.1.4 Summary

In a one-to-one comparison of handheld imaging against the vehicle scanning system, it is clear that the mobile imaging system is capable of collecting thermal imaging data in a far more scalable and efficient manner than traditional handheld thermography. Furthermore, the Essess imaging rig is equipped with multiple sensors including near infrared cameras and LIDAR, which, when combined with LWIR, allows significantly more information gathering than would be possible using traditional thermography. This includes building facade data and building orientation. The automated data processing system also allows an efficient and accurate analysis of each image, which contributes to detailed, accurate reporting. This type of quantitative analysis is not possible using the handheld system as it is impossible to accurately quantify how much energy is leaking out of one area of a building versus another area. In terms of speed, resolution, and FOV, Essess' scanning system exceeded the handheld unit by a significant margin.

5.2 Comparison of the fidelity and usefulness of imagery at varying scanning distances

Essess scanned six buildings with each building being imaged from different distances starting at 20 yards and ending at 180 yards. The resulting data showed that there is very little difference in the measured building temperature for the entire building from 20 yards versus 180 yards (± 0.16 °F). Figure 21 shows that the first pass occurred at approximately 20 yards from the building with each succeeding pass being approximately 20 yards further from the building.

Although the distance between the cameras and the building appears to have had very little effect on the system's ability to measure building surface temperatures, building feature recognition becomes more difficult as the distance from which the building is scanned is increased. Individual building leaks also become gradually less visible as the distance is increased (Figure 22).

Figure 21. Building surface temperature vs. scene distance: Temp = 23.7 ± 0.16 °F.

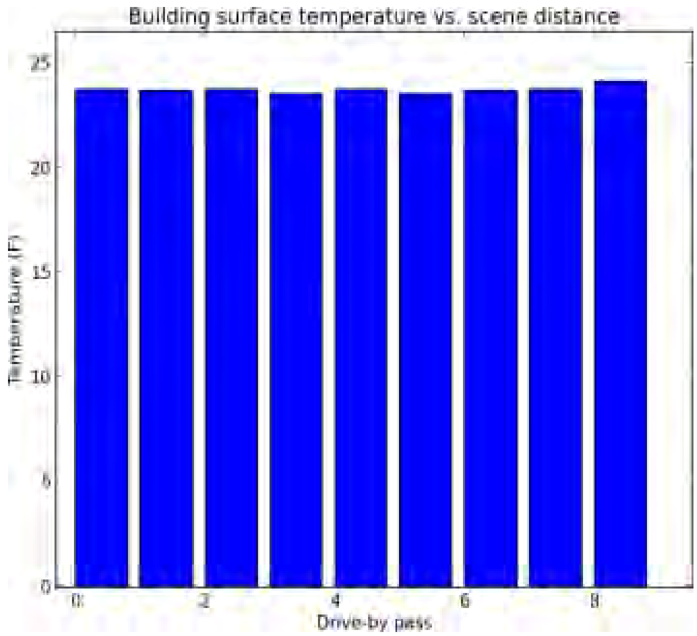
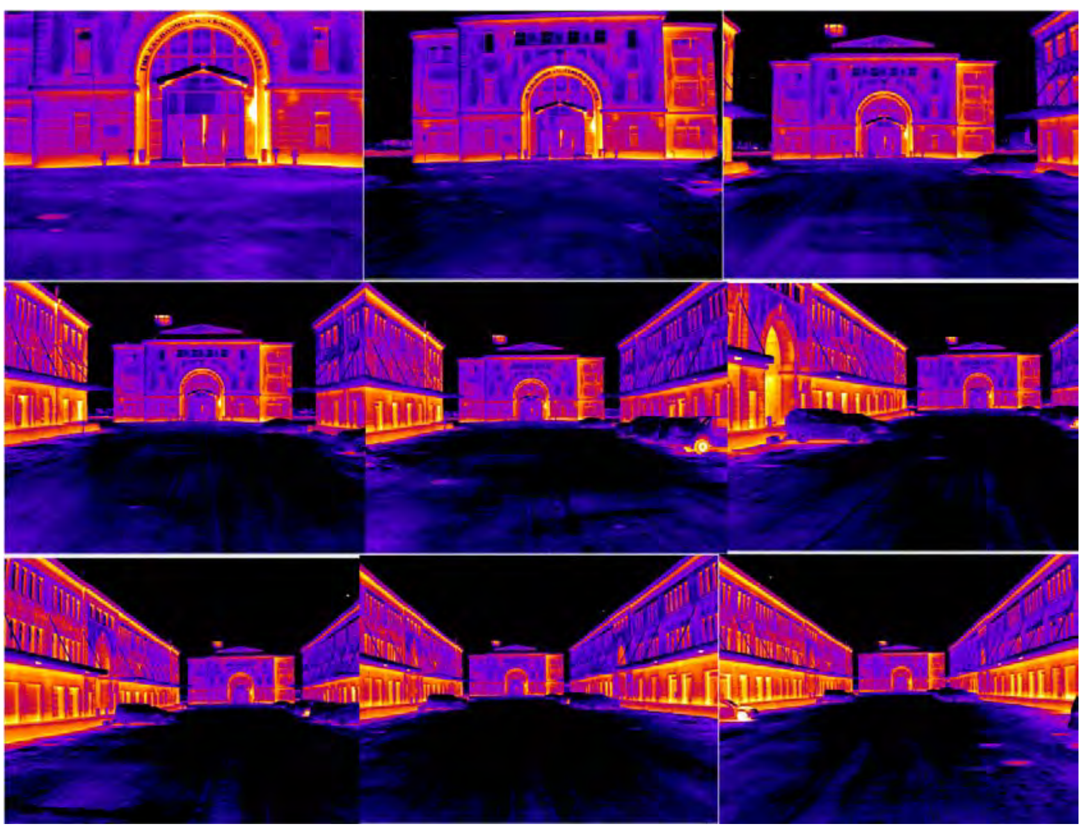


Figure 22. Essess LWIR distance test (from left to right) Row 1: 20 yards, 40 yards, 60 yards; Row 2: 80 yards, 100 yards, 120 yards; Row 3: 140 yards, 160 yards, 180 yards



5.3 Actionable results

5.3.1 Detailed analysis for Bldg 1961, Scott Air Force Base, IL

Name: USTRANSCOMM Annex
Use Type: Office
Square Footage: 80,284
Avg. Daily Electric Use: 5,694 kWh
Avg. Daily Gas Use: 63.7 therms
Electricity Score: 60th Percentile
Gas Score: 50th Percentile
Annual Cooling Load: 614,284 kWh
Annual Heating Load: 18,071 therms

The electricity and gas scores above compare the building to similarly sized buildings of the same type on an energy use per square foot basis. An energy score at the 100th percentile represents the highest energy use per square foot relative to similar buildings, while a score at the 0th percentile represents the lowest. The annual cooling and heating loads are calculated by regressing natural gas bills and electric bills against degree days for each billing period to disaggregate the heating and cooling components of building energy use.

Bldg 1961 has a gas usage of 28,960 Btu per square foot per year and electricity usage of 25.9 kWh per square foot per year.

Bldg 1961 serves as an interesting example of how energy use per square foot is not always a good predictor of leakiness or remediation potential. The building is perhaps the most obviously incompletely insulated building on the base, with numerous large hot spots scattered all over the exterior. However, its gas score only puts it in the 50th percentile, meaning that about half the buildings of a similar square footage have higher gas usage per square foot. The electricity use is a similarly middling 60th percentile.

Figure 23. ECM profile for Bldg 1961, Scott AFB.

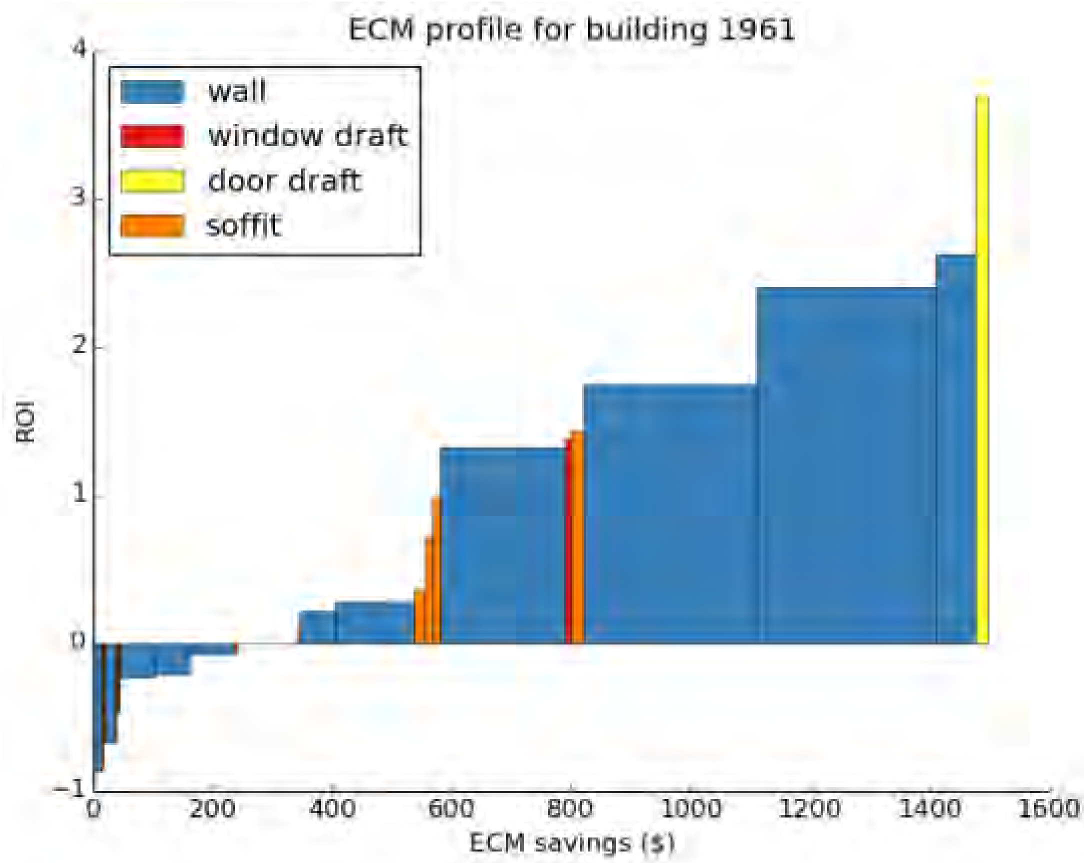


Figure 23 shows an abatement curve for all identified remediation measures for Bldg 1961, Scott AFB. Each bar represents a distinct remediation. The width of the bars represents the savings potential, while the height represents the economic viability (represented by ROI). The height of each bar shows how many dollars of savings may be expected for every $1 spent on that particular remediation measure.

Table 5 lists the recommended envelope ECMs for Bldg 1961. Annual potential remediation savings for this building are $1,156 and simple payback is 6.5 years for this package of envelope-related ECMs.

Table 5. Envelope ECMs, Bldg 1961, Scott Air Force Base.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Improve Wall Insulation	714	1721	1055	6818	6.5
Improve Soffit Insulation	47	114	70	612	8.8
Seal Door Frame Leaks	14	34	21	66	3.2
Seal Window Frame Leaks	7	17	10	66	6.3

5.3.2 Notable leaks

There is a sizable patch of poorly insulated wall on the second story of the building around timestamp 42:55. The soffit also appears to be highly emissive (Figure 24).

This is another view of the same building, showing the patch of poorly insulated wall on the second story of the building around timestamp 42:55 (Figure 25). The highly emissive soffit is more visible in this image.

Figure 24. Poorly insulated wall for Bldg 1961, Scott AFB.

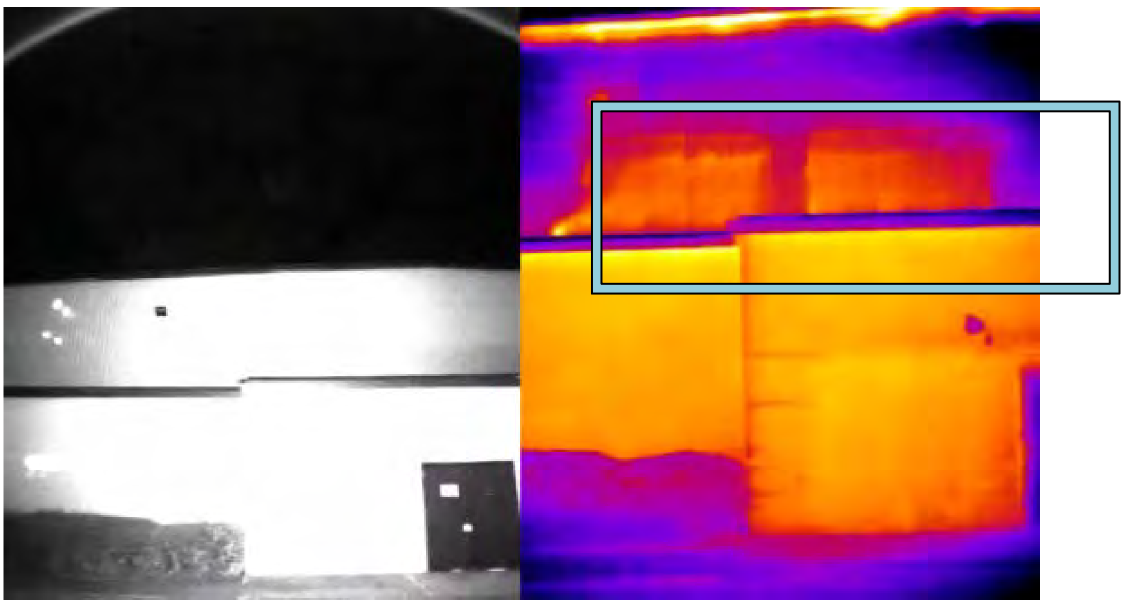


Figure 25. Various wall insulation gaps for Bldg 1961, Scott AFB.

There are numerous wall insulation gaps around the back of the same building around timestamp 43:11, as well as a leaky soffit (Figure 26).

Figure 26. Rearview of Bldg 1961, Scott AFB.

The back of the building around timestamp 43:31 is particularly emissive, with large amounts of heat leaking out. The wall has apparent insulation issues (Figure 27).

Figure 27. Large wall leaks for Bldg 1961, Scott AFB.

Similar large leaks are seen on the wall at timestamp 43:32. The "patchy appearance" indicates inconsistent insulation throughout the wall. The double doors to the right of the image may also have notable convective leaks around the frame.

5.3.3 Portfolio strategy analysis for Scott Air Force Base, IL

The analysis of Scott AFB thermal imaging data resulted in an estimated $304,393 in potential annual building envelope-related savings across all buildings on the base for remediation measures that have a payback period of 15 years or less. These savings would require approximately $2,211,500 in capital expenditures for remediation. The recommended measures include retrofitting of walls, soffits, and roof insulation and sealing leaks around windows and doorframes. Total savings from these remediation measures could save Scott AFB approximately $4,385,376 over the lifetime of the projects (15 years on average), and the measures would pay for themselves after 7.3 years. These savings result from the subset of remediation measures with a payback period of 15 years or less, while annual savings reflect all measures with positive savings independent of the remediation costs.

These base-level savings are estimated by multiplying the calculated savings for each building by the percent of the building imaged, assuming that the portions of the building not imaged are similar in characteristics (R-values, infiltration) to the portion imaged. The area of the buildings captured in the street-view thermal images identified $113,264 in savings from discrete building component leaks, at a cost of $824,985 and with a payback period of 7.3 years. The total savings over the lifetime of the envelope remediation projects identified in the thermal images was $1,612,845.

Table 6 lists the potential savings and payback period for each category of envelope-related remediations for all imaged buildings at Scott AFB.

Table 6. All recommended envelope-related remediations, Scott AFB.

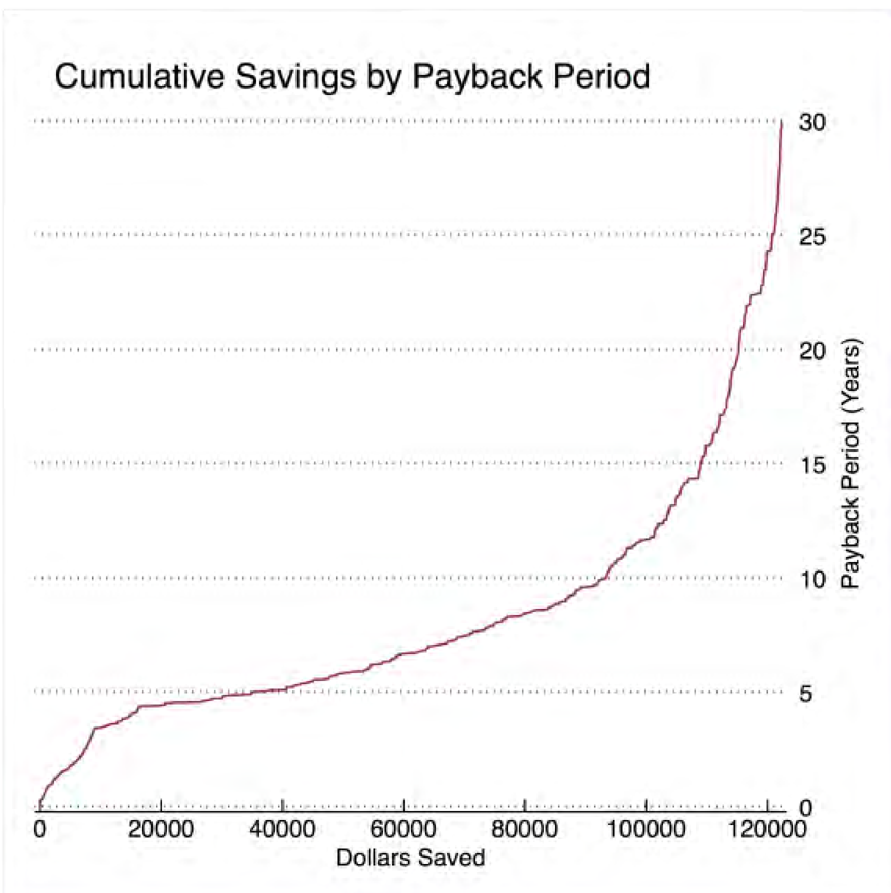
Measure	Potential Savings	Payback Period
Door Frame Leaks	$3,376	2.2
Window Frame Leaks	$8,507	3.2
Basement Wall Insulation	$2,281	7.6
Wall Insulation	$93,905	7.7
Soffit Insulation	$2,582	9.6
Roof Insulation	$2,614	11.0

Of all envelope remediation options examined, air sealing of doors and window frames tend to be the most cost effective, with a typical payback period of 2.2 years for door frames and 3.2 years for window frames. Table 6 lists both estimated base-wide potential savings for identified components and the payback period for all measures considered.

A significant portion of envelope-related remediation savings comes from improving wall insulation. This is to be expected, as walls comprise the majority of the surface area of most buildings on the base. Wall insulation retrofits can be cost effective for the more emissive surfaces, and the thermal imaging data can help provide an essential pre-assessment to determine the surfaces to target for improvements.

The total savings available at each different payback period may be examined by reviewing the cumulative savings across all measures by payback period (Figure 28).

Figure 28. Dollars saved versus payback period (years).



Calculated potential annual savings resulting from envelope-related remediation of imaged surfaces were $35,000 with a payback period of less than 5 years, over $93,000 in savings with a payback of less than 10 years, and over $113,000 in savings with a payback of less than 15 years.

5.3.4 Recommendations for Scott Air Force Base, IL

Table 7 lists the high-impact cost-effective remediation measures that base planners should target first. These are primarily wall insulation-related measures for the buildings identified as the most emissive. These 30 measures would collectively save an estimated $21,696 per year at a cost of $104,953 with a payback period of 4.8 years.

Table 7. Immediately actionable remediations for Scott Air Force Base

Label No.	Bldg No.	Action	Material	Init R Value	New R Value	Savings ($)	Cost ($)	Payback (yrs)
1	1600	Improve Wall Insulation	Brick	8.1	13.7	2509	11427	4.6
2	533	Improve Wall Insulation	Brick	8.1	13.6	1835	8337	4.5
3	1600	Improve Wall Insulation	Brick	8.4	13.6	1733	8706	5.0
4	1575	Improve Wall Insulation	Brick	8.4	13.6	1511	7694	5.1
5	1575	Improve Wall Insulation	Brick	8.0	13.7	1436	6327	4.4
6	1575	Improve Wall Insulation	Brick	8.3	13.7	1382	6721	4.9
7	40	Improve Wall Insulation	Brick	8.9	13.6	1362	8041	5.9
8	533	Improve Wall Insulation	Brick	8.2	13.6	1338	6306	4.7
9	1989	Improve Wall Insulation	Brick	8.6	13.6	1043	5628	5.4
10	1456	Improve Wall Insulation	Siding	6.9	10.0	1022	5340	5.2
11	1600	Improve Wall Insulation	Brick	8.3	13.6	865	4195	4.8
12	56	Improve Wall Insulation	Brick	8.8	13.6	732	4257	5.8
13	61	Improve Wall Insulation	Brick	8.8	13.5	650	3804	5.9
14	1644	Improve Wall Insulation	Concrete	6.1	10.0	627	2264	3.6
15	1989	Improve Wall Insulation	Brick	8.7	13.5	622	3559	5.7
16	1989	Improve Wall Insulation	Brick	8.4	13.6	586	2975	5.1
17	3296	Improve Wall Insulation	Brick	8.1	13.7	555	2519	4.5
18	5000	Improve Wall Insulation	Brick	8.7	13.7	552	3070	5.6
19	5022	Seal Window Frame Leak	Roof	10.0	15.0	227	66	0.3
20	1989	Improve Roof Insulation	Soffit	8.4	13.7	227	1642	7.2
21	1575	Improve Soffit Insulation	D Frame	N/A	N/A	147	775	5.3
22	1650	Seal Door Frame Leak	W Frame	N/A	N/A	117	66	0.6
23	1530	Seal Window Frame Leak	Soffit	8.6	13.7	113	66	0.6
24	1987	Improve Soffit Insulation	W Frame	N/A	N/A	94	538	5.7
25	10	Seal Window Frame Leak	W Frame	N/A	N/A	82	66	0.8
26	8	Seal Door Frame Leak	D Frame	N/A	N/A	73	66	0.9
27	1650	Seal Door Frame Leak	D Frame	N/A	N/A	70	66	0.9
28	1600	Seal Window Frame Leak	W Frame	N/A	N/A	68	66	1.0
29	3189	Seal Door Frame Leak	D Frame	N/A	N/A	67	66	1.0
30	5000	Improve Soffit Insulation	Soffit	8.7	13.6	51	299	5.9

Figures 29 to 35.show the specific location of all 30 immediately actionable recommendations. Note that only the primary feature (e.g., the brick wall) is analyzed in the images. Obstructions like trees or flagpoles and unrelated features such as garage doors or windows are excluded.

Figure 29. Scott AFB Bldgs 1600 (upper left), 533 (upper right), 1600 (lower left), and 1575 (lower right).

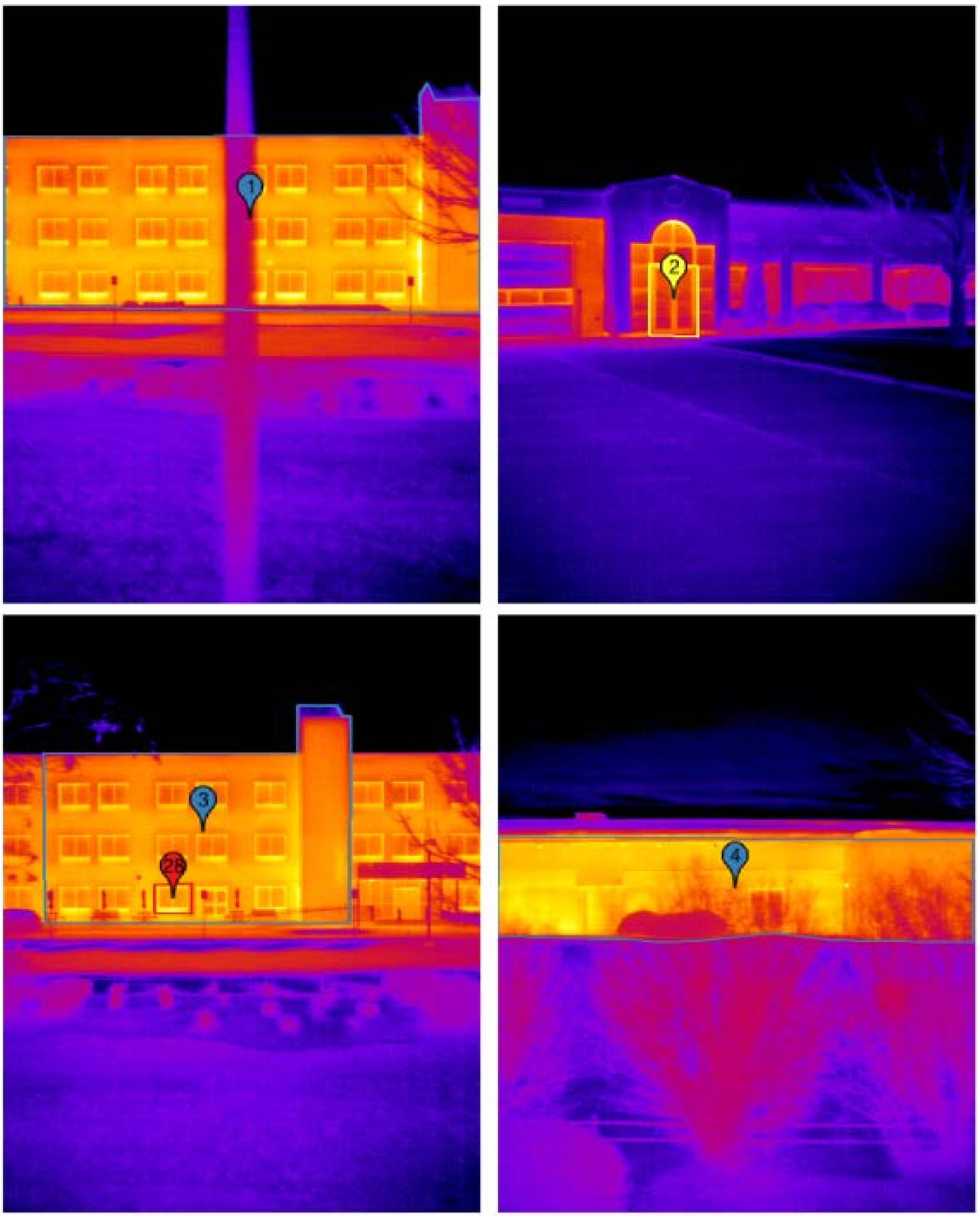


Figure 30. Scott AFB Bldgs 1575 (upper left), 1575 (upper right), 40 (lower left), and 533 (lower right).

Figure 31. Scott AFB Bldgs 1989 (upper left), 1456 (upper right), 1600 (lower left), and 56 (lower right).

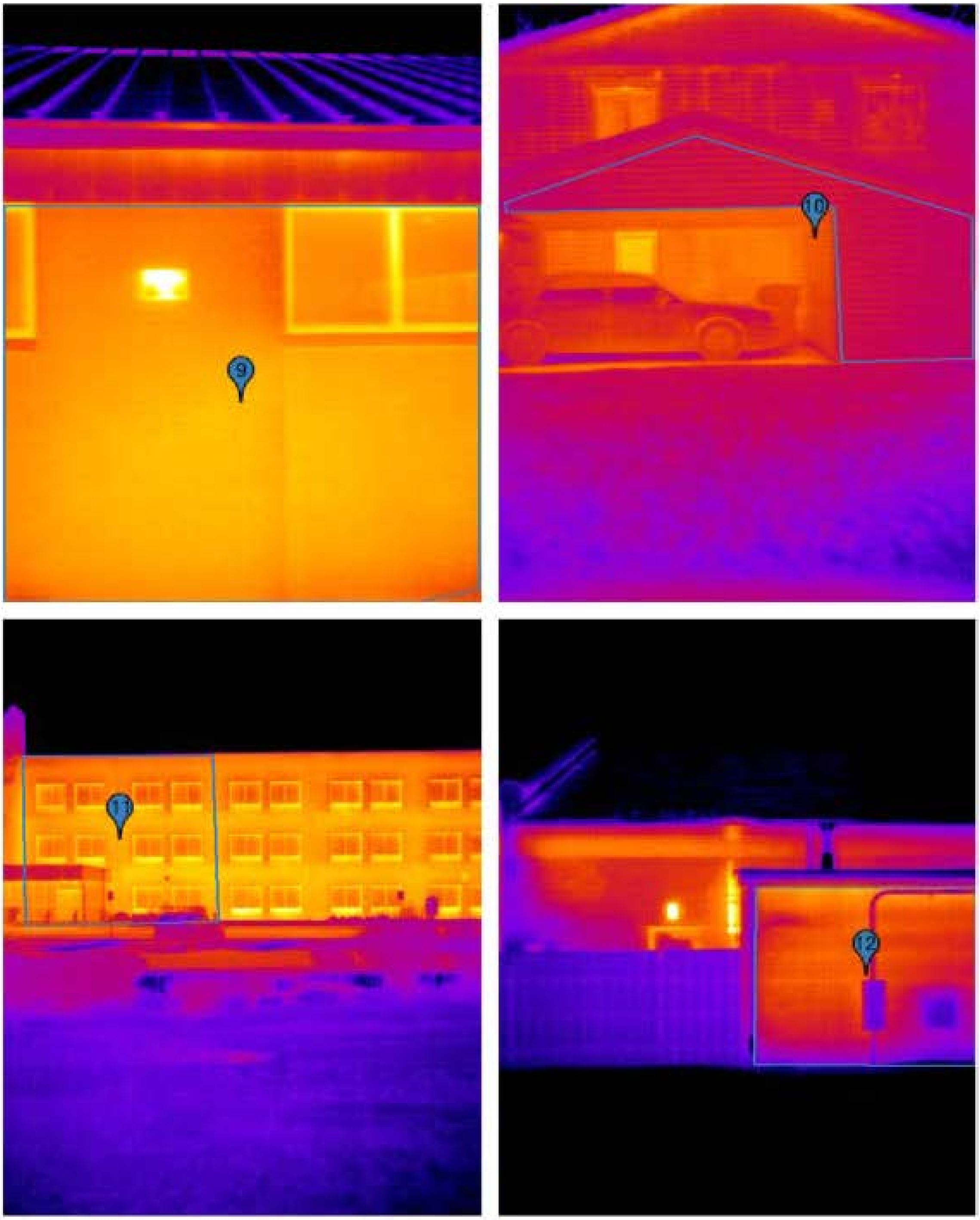


Figure 32. Scott AFB Bldgs 61 (upper left), 1644 (upper right), 1989 (lower left), and 1989 (lower right).

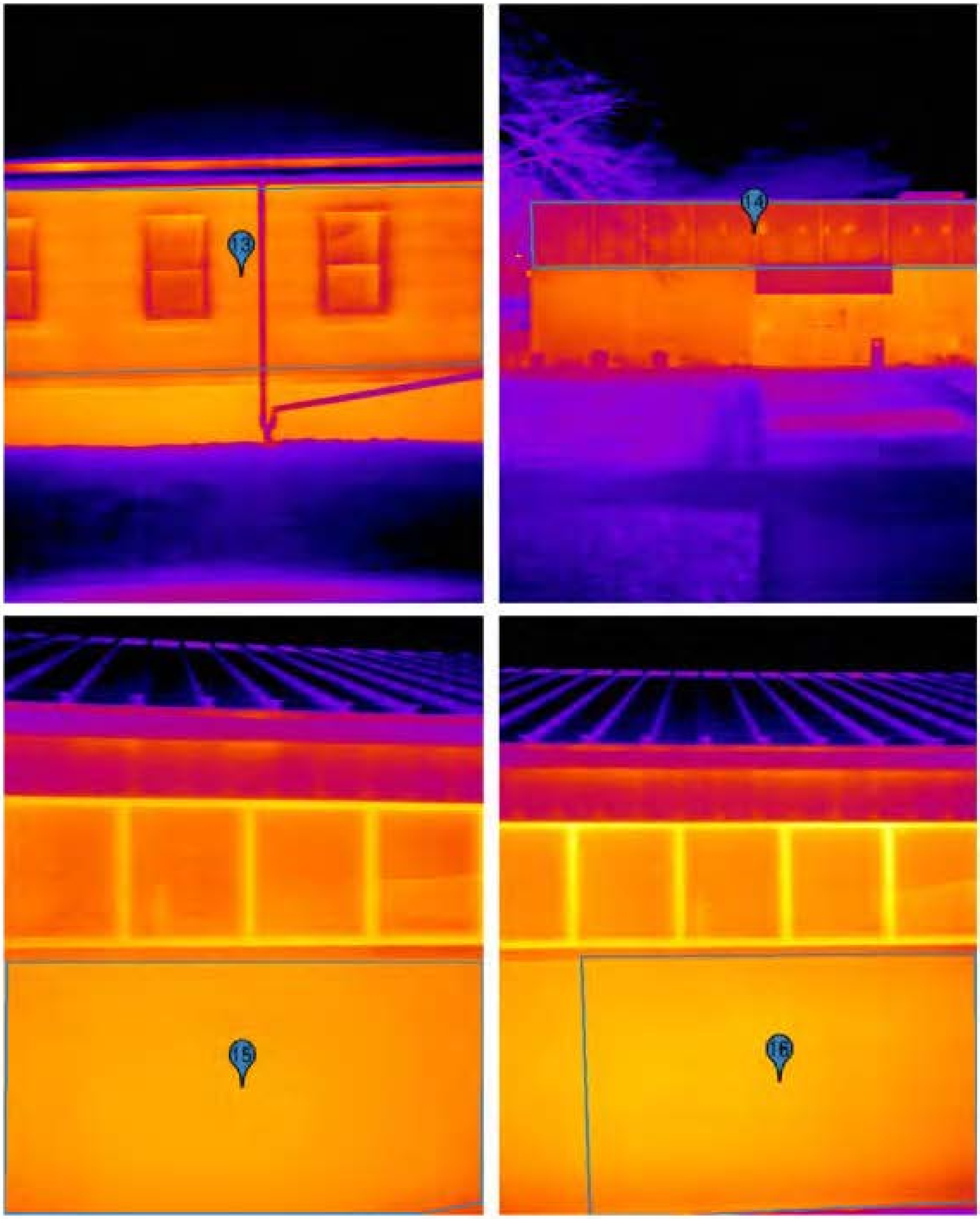


Figure 33. Scott AFB Bldgs 3296 (upper left), 5000 (upper right), 5022 (lower left), and 1575 (lower right).

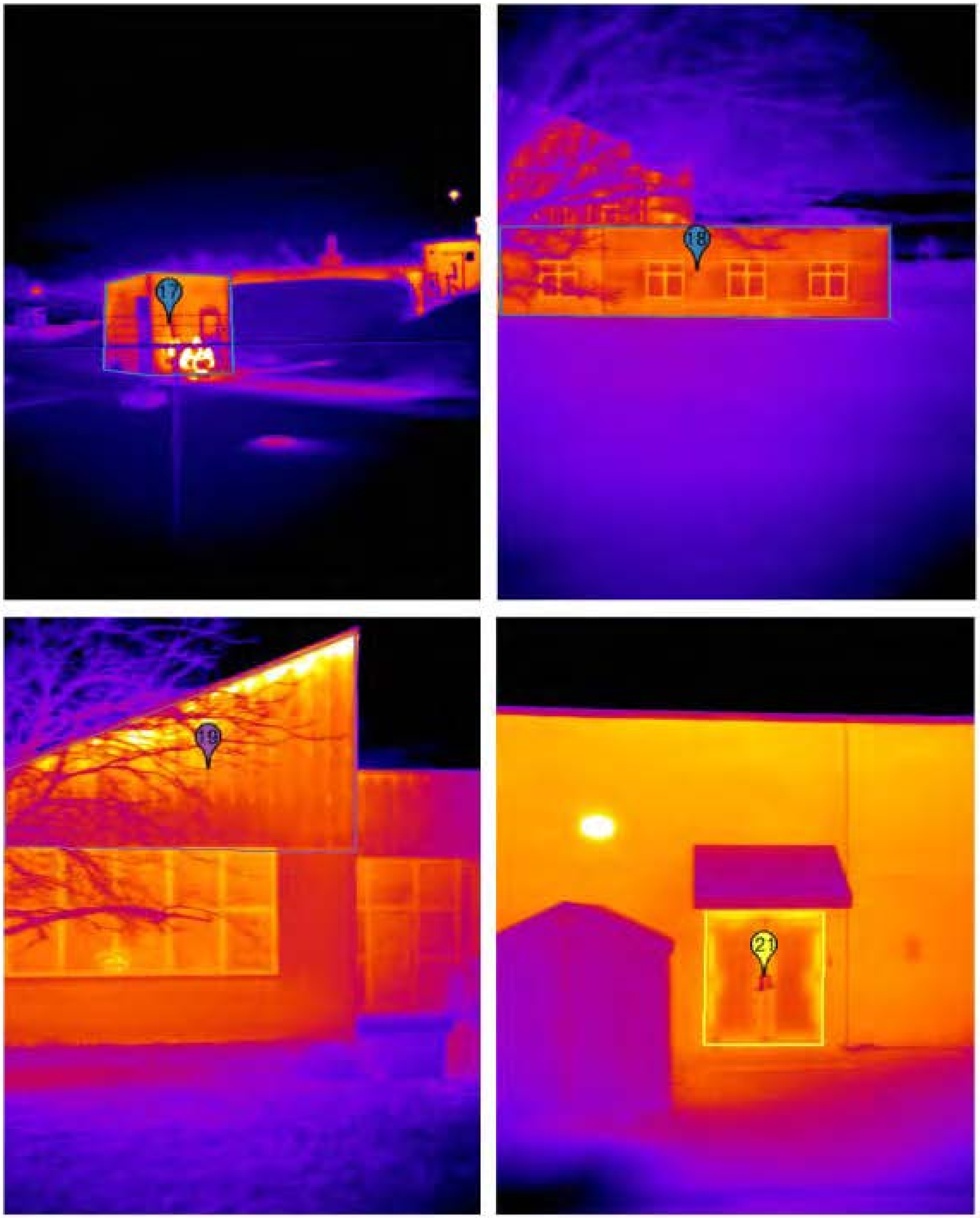


Figure 34. Scott AFB Bldgs 1650 (upper left), 1530 (upper right), 1987 (lower left), and 10 (lower right).

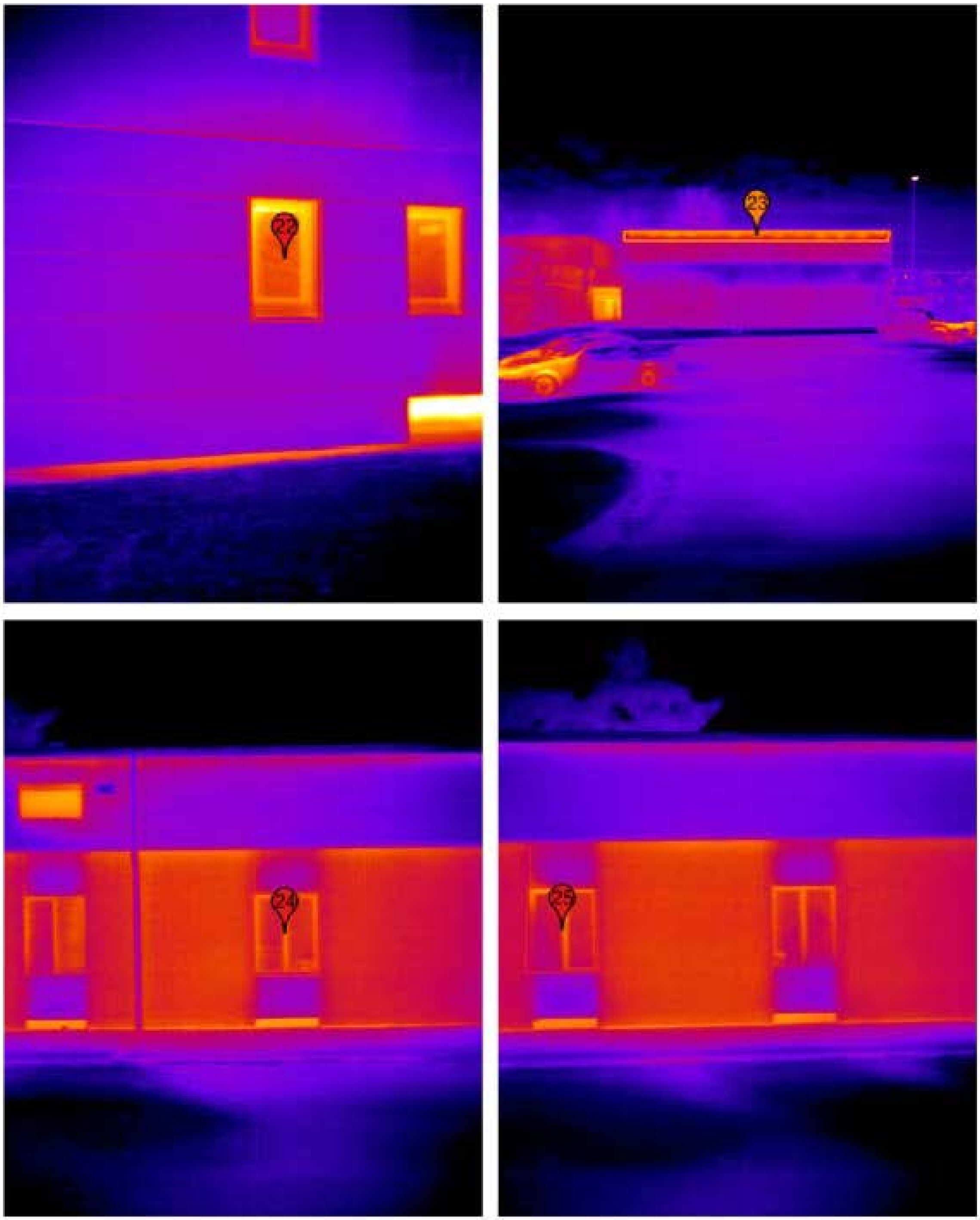
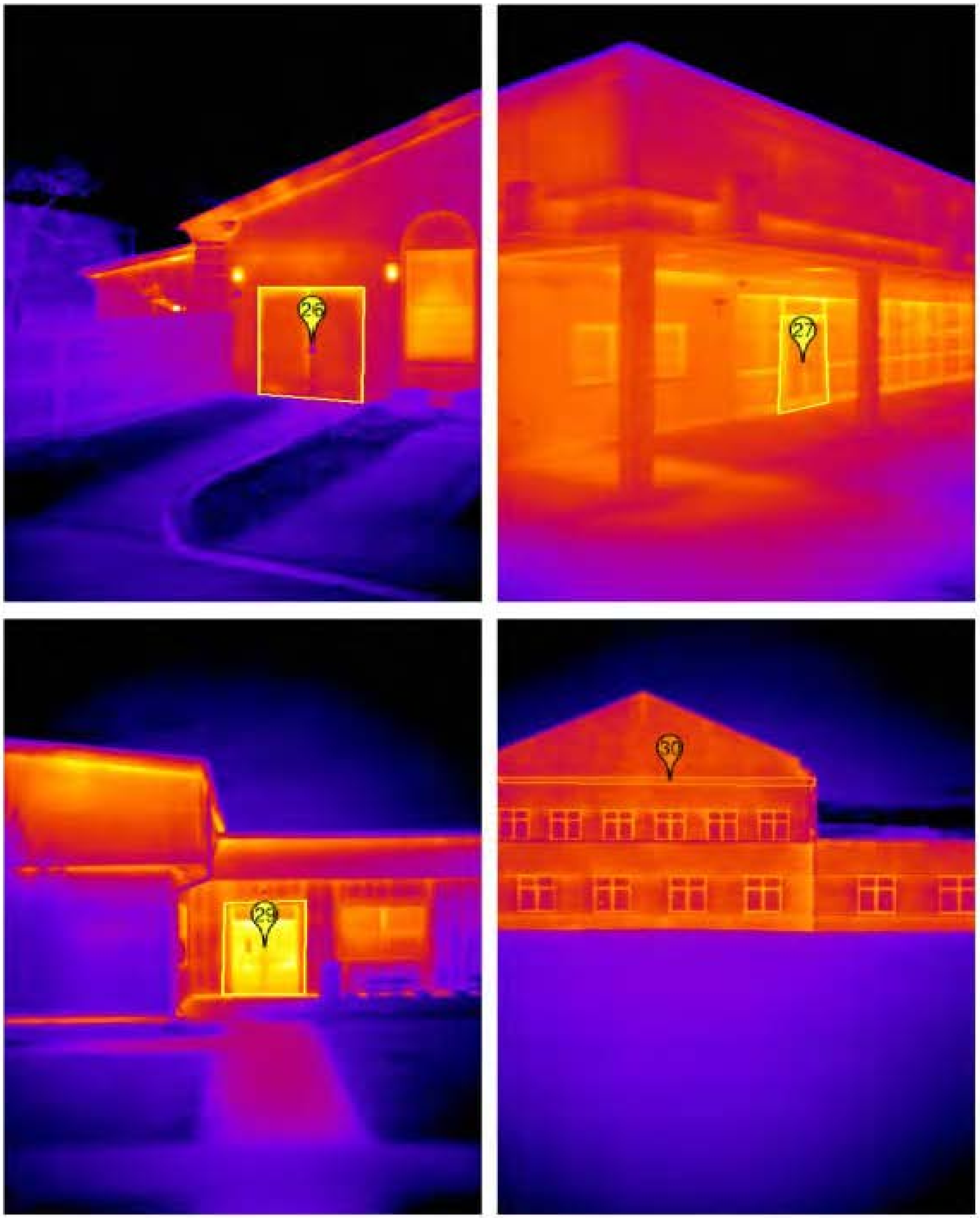


Figure 35. Scott AFB Bldgs 8 (upper left), 1650 (upper right), 3189 (lower left), and 5000 (lower right).



6 Cost Assessment

The total cost for scanning, analyzing and producing a report for this project, which included Camp Lejeune and Scott AFB, was $404,577. For the purposes of this demonstration both installations were treated as a single project and the costs were broken up by phases rather than a per-building cost. Figure 36 shows the itemized cost breakdown.

Figure 36. Essess cost summary for scanning, analysis and reporting for Camp Lejeune, NC and Scott AFB, IL.

Essess, Inc.
Budget Summary

	Phase One(1)	Phase Two(2)	Phase Three(3)	Total Phases One thru Three
Direct Labor	$33,392	$44,144	$30,008	$107,544
Fringe Benefits	$2,109	$2,732	$1,707	$6,547
Equipment Costs	$0	$0	$0	$0
Expendable Supplies	$0	$0	$0	$0
Travel	$0	$9,781	$0	$9,781
Subcontracts	$38,400	$72,000	$48,000	$158,400
Other Direct Costs	$0	$0	$0	$0
Indirect Costs	$29,821	$39,376	$26,641	$95,837
	$103,721	$168,032	$106,356	$378,109
Operating Margin (7%)				$26,468
Total Budget				$404,577

Notes:
1) See "1. Phase One Budget" for details
2) See "2. Phase Two Budget" for details
3) See "3. Phase Three Budget" for details
4) See "4. Phase Four Budget" for details
5) See "5. Phase Five Budget" for details
6) See "6. Phase Six Budget" for details

6.1 Cost model

The subtasks accomplished in each phase are outlined in detail in Section 4.1.6 (“Test Phases,” p 26). For all three phases, the majority of the costs were for direct labor and contracting Subject Matter Experts for computer vision aided data processing using commercial thermography and energy modeling. Phase 1 costs related to the customization of the imaging hardware and creating logistics software for the driving team to navigate while imaging. To capture data in the most efficient manner, the driving team was guided by an onboard navigation system with route guidance based on the installations' street network. This must be created for each base, as complete road network information for military installations is rarely publicly available. For Camp Lejeune and Scott AFB the Phase 1 costs were $103,721 (Figure 36).

Phase 2 costs were related to data capture and analysis. Essess drove the imaging vehicle to Camp Lejeune and Scott Air Force Base and captured thermal, NIR, LIDAR, and GPS data. Once the data were sent to Essess headquarters, they were processed (the raw data were converted into temperature images and the temperature images were correlated to the correct GPS coordinates based on vehicle GPS and military provided GIS information). After the data were processed, the second part of Phase 2 analyzed the processed data to detect building thermal inefficiencies and leaks in the building envelope. The contractor also built an online Drive-by Application to enable Energy Managers at Camp Lejeune and at Scott Air Force Base to select buildings for further analysis. The total cost for Phase 2 was $168,032.

Phase 3 consisted of aggregating the mobile thermal imaging results, analyzing the handheld thermography data, and preparing a Final Report for the sponsor (Environmental Security Technology Certification Program [ESTCP]). The total cost for Phase 3 was $106,356.

Table 8 lists "model" costs for a single military installation. Essess could image hundreds of installations in a single winter while maintaining the same cost structure making the technology significantly more scalable.

Table 8. Cost model for imaging a military installation.

Cost Element (for Single Military Installation)	Estimated Costs
Phase 1: Hardware Customization and Logistics Software Optimization	$51,861
Phase 2: Data Capture, processing and Analysis	$81,567
Phase 3: Aggregating analyzed data in a report format	$50,744

6.2 Cost drivers

There are no major cost drivers for this technology as it is applicable to military bases across various ASHRAE Climate Zones. The technology is efficient and scalable, which allows Essess to image bases significantly larger than Scott AFB without increasing the cost structure. However, unlike a typical auditor that charges per building, Essess' cost structure is on a per installation basis. This is due to the fact that the bulk of Essess' costs are front-loaded. Once the imaging rig is deployed to an area, there is only a marginal cost in imaging 100 buildings versus 1,000 buildings.

6.3 Cost analysis and comparison

Essess' thermal imaging, data processing, data analysis and reporting costs are roughly $200,000 per military installation. As described in the Section 6.1 ("Cost Model," p 70), the operational implementation of the technology requires significant customization to the hardware rig and to the logistics, processing and analysis software. The data in Chapter 5 ("Performance Assessment") provide a detailed description of remediation recommendations and life-cycle costs for each remediation. The end result is valuable energy efficiency data and remediation recommendations.

Traditionally, the only way to get envelope efficiency information for each building was to use a handheld thermal camera on each building. However, handheld thermography is relatively very inefficient and also requires a human to interpret each image whereas Essess has the ability to automatically analyze thousands of thermal images. Furthermore, commercial energy audits that include envelope thermal imaging using handheld thermography typically cost around $0.20 per sq ft of building floor area (based on data from local thermal imaging auditors within 100 miles of Scott AFB and Green-Buildings.com). Essess imaged 4.6 million sq ft of building space at Scott AFB. Based on the costs above, having the same amount of building space analyzed with a handheld camera would have cost approximately $920,000 for Scott AFB. That is about $720,000 more than Essess' mobile imaging costs.

7 Implementation Issues

The Essess imaging rig is proprietary technology that was deployed based on a licensing model so there was (and will be) no turnover of hardware, software, or intellectual property to the Government. However, Air Force installations can take advantage of this technology by contracting directly with Essess.

This technology is limited to scanning the street sides of buildings. As a result, for most buildings, four sides of the buildings will not be scanned. Two or three sides are typically scanned depending on the orientation of a building relative to the street. This technology is also limited by the requirement to have a ΔT between building interior and exterior ambient temperatures of at least 20 °F, so scanning must occur when nighttime temperatures are below 50 °F. This limits application of this technology to regions where there is at least 1 week of the year in which nighttime temperatures are below 50 °F. Most regions of the United States fall within this boundary condition. Adjustments are made for empty buildings or buildings where there is no internal heating and no way of knowing the internal temperature setpoint (discussed in Section 4.3.3). This technology is somewhat hindered by trees, bushes and other obstructions that might partially obscure a clear view of a building's envelope from the street. However, the automated data processing pipeline developed by Essess to take the scanned data and prepare it for a report format corrects for these kinds of obstructions in a number of ways that have been tested by Essess.

8 Conclusion

This demonstration validated a method of rapidly and cost effectively scanning and analyzing large numbers of building envelopes, quantifying energy losses, and prioritizing energy leaks for cost-effective repairs or improvements. At Scott AFB, over 3,000 distinct building feature components were identified on buildings across the base. These features were categorized by type and by surface temperature to provide an in-depth analysis of each building's envelope energy profile. Analysis showed that over $300,000 in potential envelope-related savings per year could be achieved by implementing various envelope-related ECMs. Over the lifetime of these measures, Scott AFB has the potential to save over $4 million by investing around $2 million with a simple payback period of roughly 7 years.

At Camp Lejeune, over 2500 distinct building feature components were identified across various buildings throughout the base. Similar to Scott AFB, these features were categorized by type and surface temperature to provide an in-depth look at the energy efficiency of each building's envelope. This quantified analysis showed that Camp Lejeune could save over $100,000 per year by implementing ECMs outlined in this report. The total investment would be less than $1 million, but would allow the base to save nearly $1.7 million over the lifetime of the measures with a simple payback period of less than 9 years. For both installations, the analysis assumes a cost per kWh of $0.056 and cost per therm of $0.59.

This work also concludes that Facilities Engineers at other DoD installations can use this demonstrated method to cost effectively evaluate large portions of their building stock to determine the overall condition of their building envelopes and identify opportunities to repair or improve the envelopes to reduce unnecessary energy losses and improve overall energy efficiency. The demonstrated technology offers one avenue to help the DoD reach its goal of saving energy across all military installations by identifying the best candidate installations for energy-saving improvements to building envelopes, i.e., those with the highest potential savings. It would then be possible to combine that priority list with information on optimal building stocks and portfolios of cost-effective improvements to equip the DoD to save millions of dollars in energy loss.

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Acronyms and Abbreviations

Term	Definition
AFB	Air Force Base
AFUE	Annual Fuel Utilization Efficiency
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
AWS	Amazon Web Services
CEERD	U.S. Army Corps of Engineers, Engineer Research and Development Center
CERL	Construction Engineering Research Laboratory
CFM	cubic feet per minute
COR	Contract Officer Representative
DoD	U.S. Department of Defense
DR	Dead Reckoning
ECM	Energy Conservation Measure
EISA	U.S. Energy Independence and Security Act of 2007
EO	Executive Order
ERDC	U.S. Army Engineer Research and Development Center
ERDC-CERL	Engineer Research and Development Center, Construction Engineering Research Laboratory
ESTCP	Environmental Security Technology Certification Program
EW	Energy and Water
FOV	Field of Vision
GB	Gigabyte
GIS	Geographic Information System
GPS	Global Positioning System
HASP	Health and Safety Plan
HDL	High Definition LIDAR
IR	Infrared
KSR	Kinetic Super-Resolution
LBL	Lawrence-Berkeley Laboratory
LIDAR	Light Detection and Ranging
LTE	Long Term Evolution
LWIR	Long-Wave Infrared
MB	megabyte
MIPR	Military Interdepartmental Purchase Request
MIT	Massachusetts Institute of Technology
N/A	Not Applicable
NCDC	National Climatic Data Center
NIR	Near Infrared
NOAA	National Oceanic and Atmospheric Administration

Term	Definition
O&M	Operations and Maintenance
OMB	Office of Management and Budget
ORNL	Oak Ridge National Laboratory
PAX	Programming, Administration, and Execution System
PNNL	Pacific Northwest National Laboratory
QCLCD	Quality Controlled Local Climatological Database
ROI	Return on Investment
SCOW	Supply Chain Operations Wing
SD	Secure Digital
SEER	Seasonal Energy Efficiency Ratio
SF	Standard Form
TR	Technical Report
TRM	Technical Reference User Manual
USACE	U.S. Army Corps of Engineers

Appendix A: Health and Safety Plan (HASP)

Since this work requires a vehicle to drive around the installations at low speeds, the Health and Safety Plan mostly entails obeying installation traffic rules. Since the scanning vehicle will be operating at very low speeds, drivers should be careful to avoid blocking faster traffic on higher speed installation roadways. Vehicle lighting systems must be maintained in good working order. The driver(s) must take care to signal all turns and to park outside of the lane of traffic when stopping is necessary.

Appendix B: Points of Contact

Point of Contact	Organization	Phone and E-mail	Role in Project
James Miller	U.S. Army ERDC-CERL	(217) 373-4566, james.p.miller@usace.army.mil	Principal Investigator, Contract Officer Representative (COR)
Navi Singh	Essess	(857) 445-4135 Navi@essess.com	Team Leader
Elizabeth Toftemark	Scott AFB, Base Civil Engineer	(618) 256-5534 elizabeth.toftemark@us.af.mil	Deputy of Operations Engineering

Appendix C: Building Envelope Component Findings

This appendix examines specific components found in buildings around the installation, including window frames, door frames, window glass, brick walls, other walls, and soffits (generally speaking, where the wall meets the roof). These components are examined in detail, as they are all readily remediable through air sealing and insulation improvements.

C.1 Building window frames

Window frames were differentiated from window glass in the 30 buildings on the base analyzed in detail to separate out energy loss due to conduction (e.g., poorly insulated single pane windows [Figure C-1]) and convection (such as leaks through cracks around window frames). The study tagged 511 discrete window frames. The measure of leakage was expressed in cubic feet per minute per linear foot of crack. Figure C-2 shows the frequency distribution of estimated leakages across the base. Section 4.2 ("Baseline Characterization") discusses the methodology for calculating these values.

Both heating and cooling losses can be calculated once the leakage rate is estimated. Figure C-3 shows the potential remediation savings for each surveyed window. The majority of windows have a savings potential below $25 per year, with a long tail of potentially very leaky window frames. The leakiest window frames have annual savings potentials through air sealing remediation of nearly $100 per year. Over 90% of the savings potential comes via reduced space heating fuel use; cooling contributes relatively little to the estimate of potential convective leak savings, especially since latent heat associated with cooling is not explicitly analyzed.

The leakiest window frames identified on the base were in Bldgs 5022, 8, 1600, 1530, 10, and 1900.

Figure C-1. Thermal image of typical window glass thermal leaks, Scott AFB.

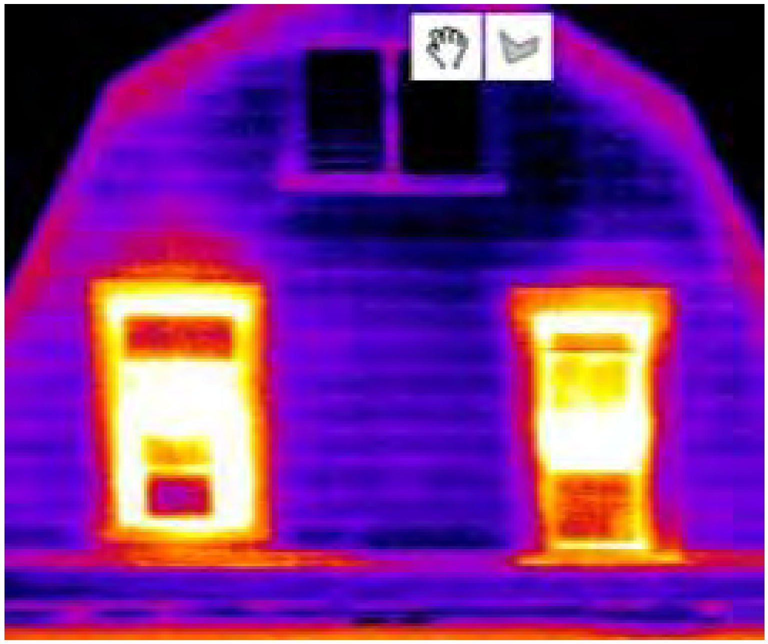


Figure C-2. Distribution of window frame leaks, Scott AFB.

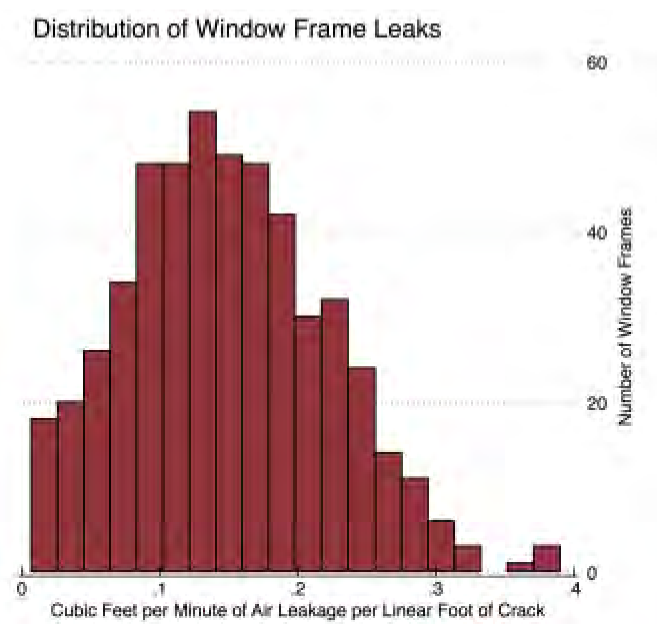
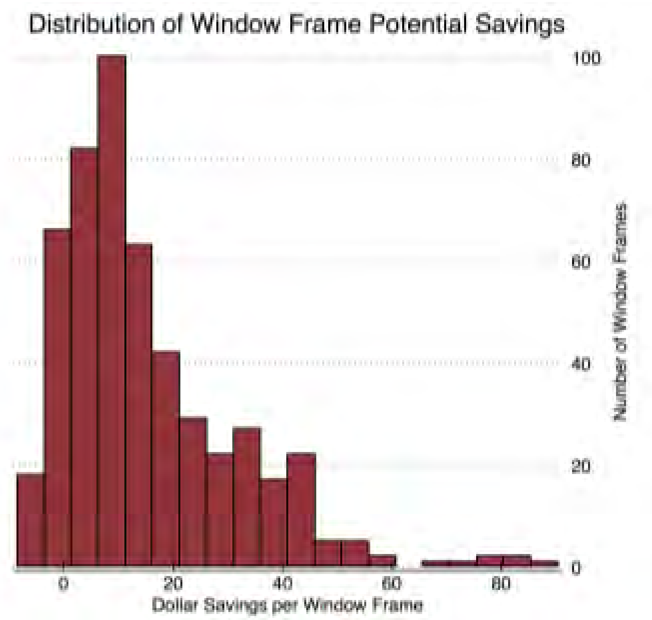


Figure C-3. Distribution of window frame potential annual energy cost savings, Scott AFB.



C.2 Building door frames

Building door frame leakage is estimated through a process similar to that used to estimate window frame leakage, by isolating the frame polygon from the door polygon and measuring the emissivity relative to other doors on the base (Figure C-4). One hundred 40 distinct door frames were identified in the 30-building detailed analysis, with a range of leakage from effectively nothing to at or above 0.4 CFM per linear crack foot (Figure C-5).

Figure C-4. Thermal image of typical door thermal energy leaks, Scott AFB.

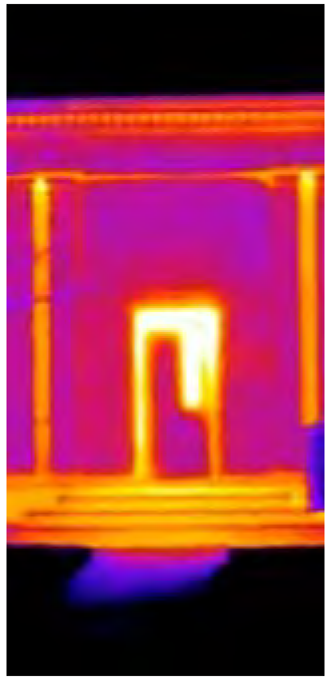


Figure C-5. Distribution of door frame air leaks, Scott AFB.

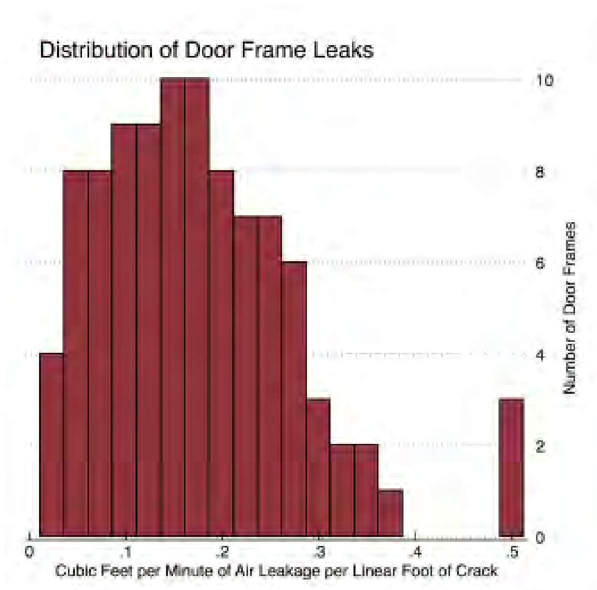
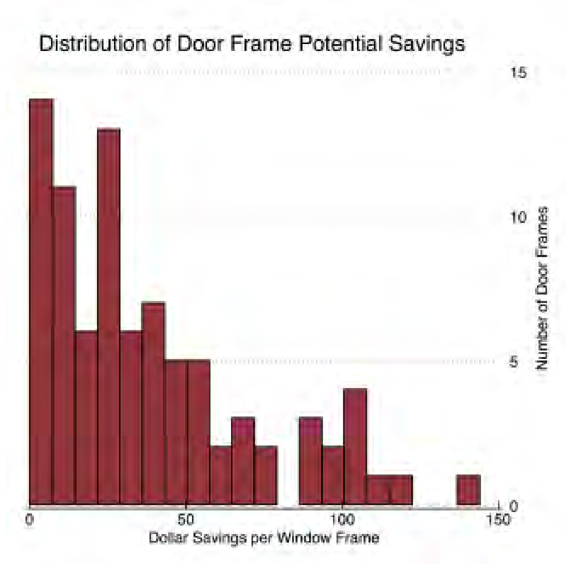


Figure C-6 shows a distribution of potential annual savings from remediation of door frame leaks, which are estimated to range from $0 to greater than $100 per year per door frame for some extreme cases. The average savings potential is about $40 per door. Remediation through the use of weather-strips and similar measures should be cost effective for most doors surveyed on the base.

Figure C-6. Distribution of door frame potential annual energy cost savings, Scott AFB.



The leakiest door frames identified on the base were in Bldgs 1650, 470, 3189, 1600, 460, and 4010.

C.3 Walls

Walls on the base were categorized as constructed of either brick, vinyl siding, or concrete. Three hundred 88 distinct brick wall polygons, 221 vinyl or other siding walls, and 77 concrete walls were identified. Costs associated with wall polygons were estimated based on their time-normalized surface temperatures (Figure C-7) and inferred R-values, as described in Section 4.2 ("Baseline Characterization"). Estimated annual heating and cooling costs from wall polygons range from $2.15/sq ft to $5.75/sq ft (Figure C-8). Brick walls in general had lower estimated costs per square foot (~$3) than did siding or concrete walls (~$4).

Figure C-7. Thermal image of a typical leaky wall, Scott AFB.

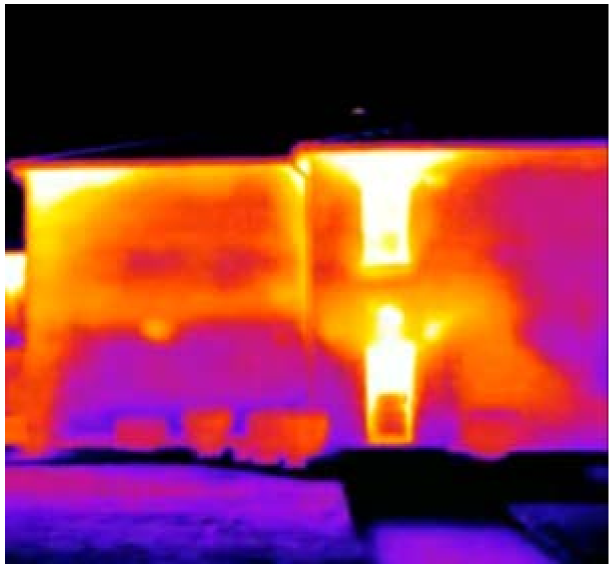
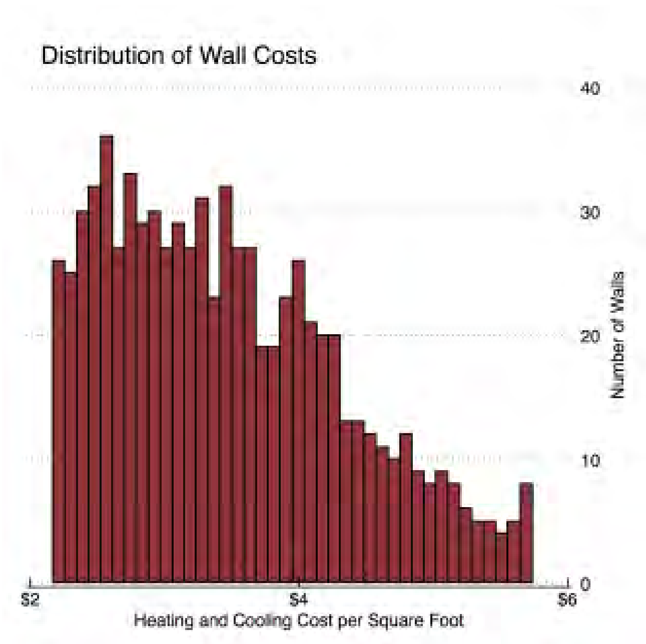
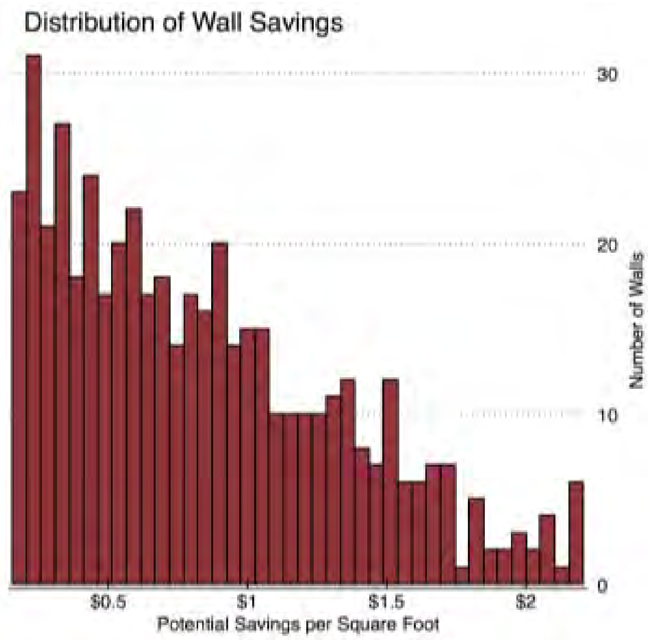


Figure C-8. Distribution of annual heating and cooling costs per square foot of wall, Scott AFB.



Potential remediation savings for walls were estimated by running the heat flow model on estimated current R-values and post-remediation R-values. Savings range from zero (or negative savings in a few cases of very well insulated walls) up to slightly over $2/sq ft (Figure C-9). At an average installation and labor cost of around $7/sq ft of wall area, walls with particularly high energy leakage are cost effective to remediate.

Figure C-9. Potential wall annual energy cost savings per square foot, Scott AFB.



Of the 777 wall polygons identified, 563 would have positive savings through improved insulation. Of these, approximately 335 would have a payback period of less than 15 years. The average savings associated with improving wall insulation for these 335 cases was around $1.08/sq ft of wall area. The most emissive walls identified on the base were in Bldgs 5029, 1456, 5713, 528, 3689, and 8040.

C.4 Roofs

Roof heat loss is calculated similarly to wall heat loss by looking at time-normalized surface temperatures (Figure C-10). The system identified 211 distinct roof polygons. (Note that a single roof will usually have more than one polygon identified, as the maximum size of a polygon is dictated by the FOV of the camera in a single image frame.) The estimated heating and cooling cost associated with these roofs ranged from $1.75 to $3.44/sq ft of roof area (Figure C-11).

Figure C-10. Example of a thermally leaky roof, Scott AFB.

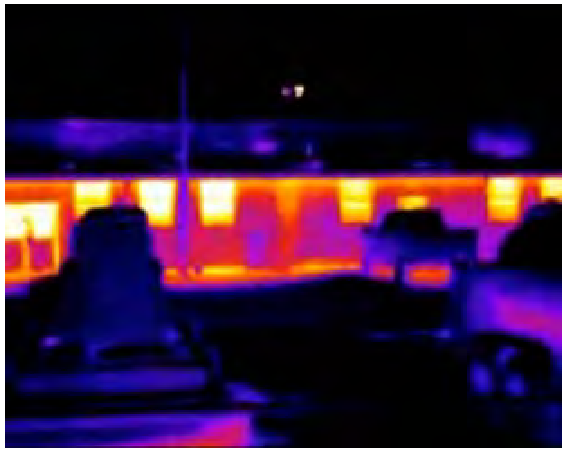
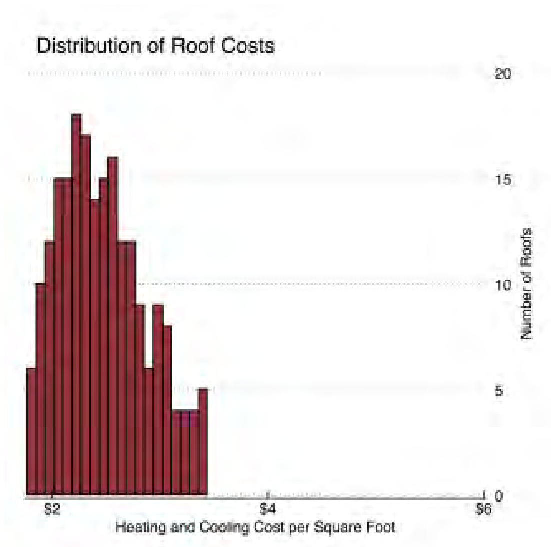
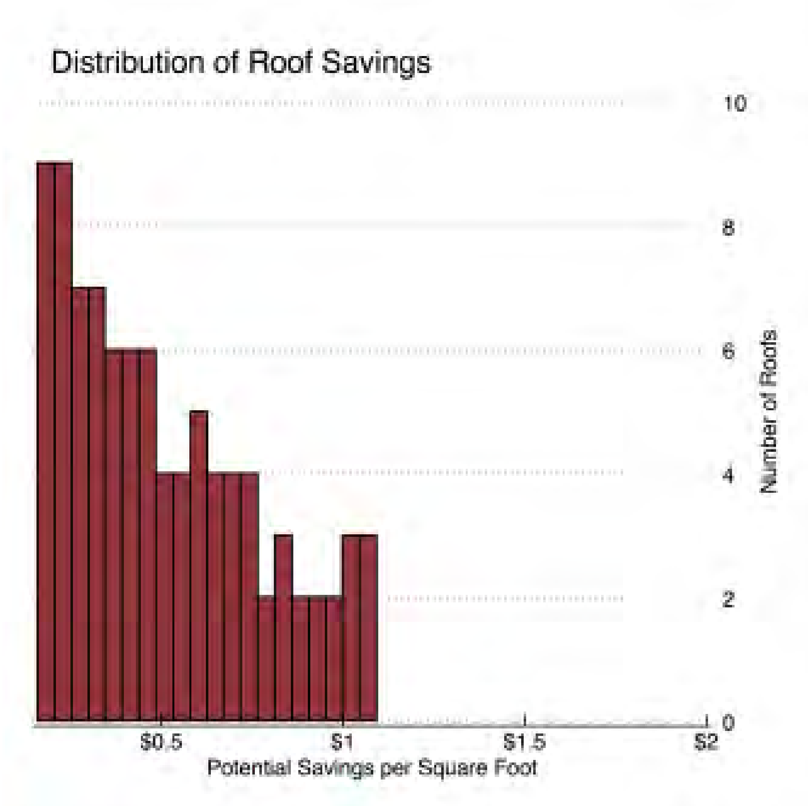


Figure C-11. Distribution of roof annual heating and cooling costs per square foot, Scott AFB.



One hundred nineteen identified roof polygons had positive remediation savings, with 38 having paybacks of less than 15 years. The average savings associated with improving roof insulation for these 38 cases was around $0.78/sq ft. The most emissive roofs identified on the base were on Bldgs 1635, 1640, 5713, 1512, 861, and 1441. Figure C-12 shows a distribution of potential roof annual heating and cooling savings associated with remediating roof energy leaks.

Figure C-12. Distribution of roof annual heating and cooling cost savings per square foot, Scott AFB.



C.5 Soffits

Soffits are areas where the wall meets the roof and are often spots where insulation is poor and air leaks are more common (Figure C-13). The system identified 282 total soffit polygons on buildings on the installation. Their R-values were estimated based on surface temperatures similar to the calculation for walls and roofs. The average annual heating and cooling costs resulting from soffit energy leakage range from $2.15 to $4.30/sq ft (Figure C-14).

Of the 194 soffit polygons that had positive remediation savings, 96 had paybacks of less than 15 years. The average savings associated with improving soffit insulation for these 96 cases was around $0.99/sq ft. Figure C-15 shows a distribution of potential annual heating and cooling savings due to soffit improvements. The most emissive soffits identified on the base were on Bldgs 1650, 1987, 5000, 624, 755, and 60.

Figure C-13. Typical leaky soffit, Scott AFB.

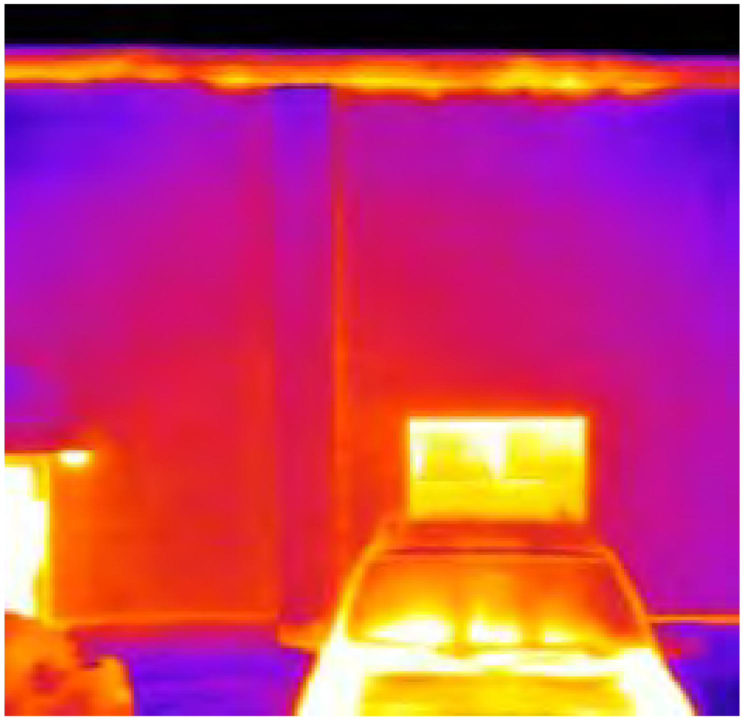


Figure C-14. Distribution of annual heating and cooling costs per square foot due to soffit leaks, Scott AFB.

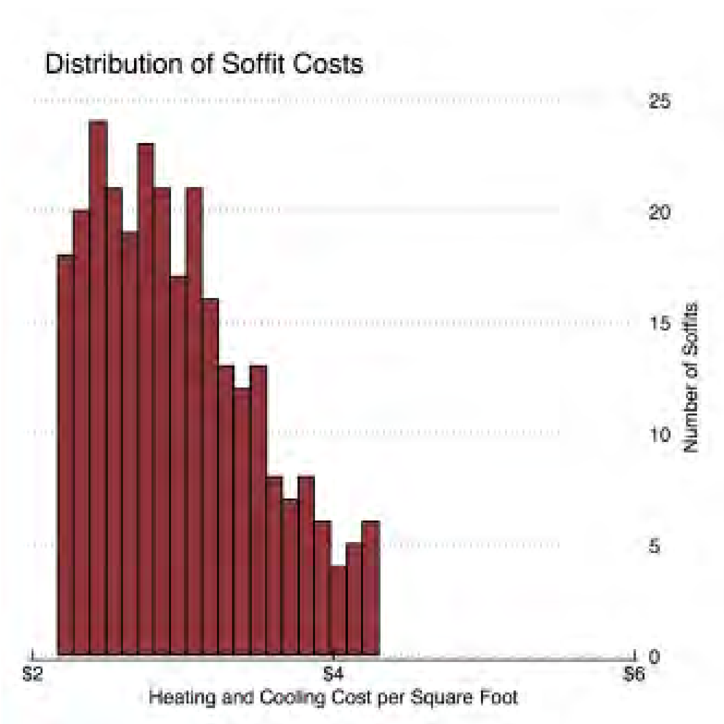
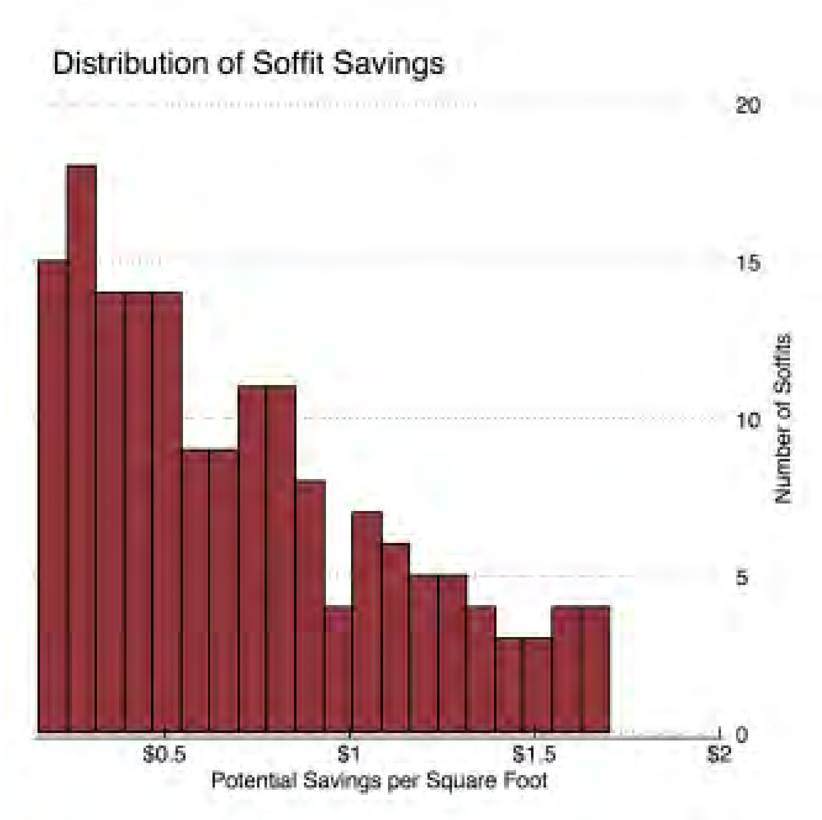


Figure C-15. Distribution of potential annual heating and cooling cost savings due to soffit improvements, Scott AFB.



Appendix D: Detailed Analysis of 30 Buildings at Scott AFB, IL

D.1 Bldg 5

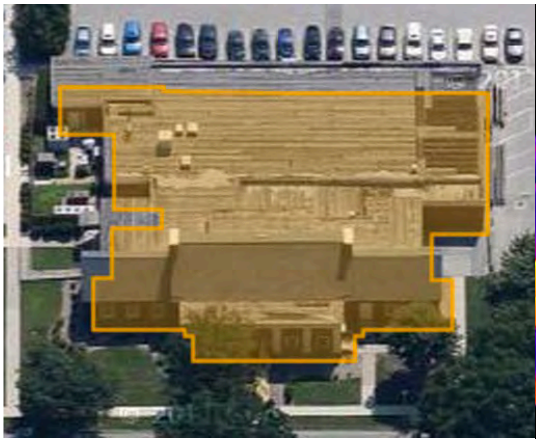
D.1.1 Description of Bldg 5, Scott AFB

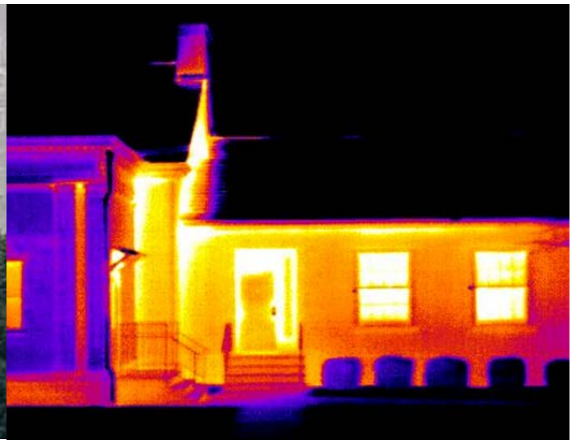
Name: Comm. Facility
Use Type: Office
Square Footage: 17,927
Avg. Daily Electric Use: Not Provided
Avg. Daily Gas Use: 16.8 therms
Electricity Score: N/A
Gas Score: 45th Percentile
Annual Cooling Load: N/A
Annual Heating Load: 1,841.9 therms

Bldg 5 (Figures D-1 and D-2) has an annual natural gas usage of 34,197 Btu/sq ft. (No electricity data were available for analysis.) The electricity and gas scores above compare the building to similarly sized buildings of the same type on an energy use per square foot basis. An energy score at the 100th percentile represents the highest energy use per square foot relative to similar buildings, while a score if the 0th percentile represents the lowest. The annual cooling and heating loads are calculated by regressing natural gas bills and electric bills (when available) against degree days for each billing period to disaggregate the heating and cooling components of building energy use.

Figure D-1. Aerial view of Bldg 5, Scott AFB.

Figure D-2. Thermal image of Bldg 5, Scott AFB.





D.1.2 Notable leaks at Bldg 5, Scott AFB

Figure D-3. NIR image (left) and thermal image (right) of Bldg 5, Scott AFB.

The section of wall at 63:02 in the Drive-by Application (Figure D-3, center of the right picture above as outlined by the blue rectangle) has a notable warm spot that does not correspond with any differentiable feature in the near IR. This may indicate a poorly insulated part of the brick wall, and may be worth investigating further.

The NIR image in Figure D-4 shows that the door frame in the IR image at 63:16 in the Drive-by Application is fairly emissive. The soffit (where the roof meets the wall) also appears abnormally warm. These areas should be investigated further and addressed immediately.

Figure D-4. NIR image (left) and thermal image (right) of Bldg 5, Scott AFB. Highly emissive door frame shown in polygon at the right.

D.1.3 Envelope ECMs for Bldg 5, Scott AFB

Figure D-5 shows the relative ROI for envelope ECMs for Bldg 5, Scott AFB.

Figure D-5. Envelope ECM profile for Bldg 5, Scott AFB.

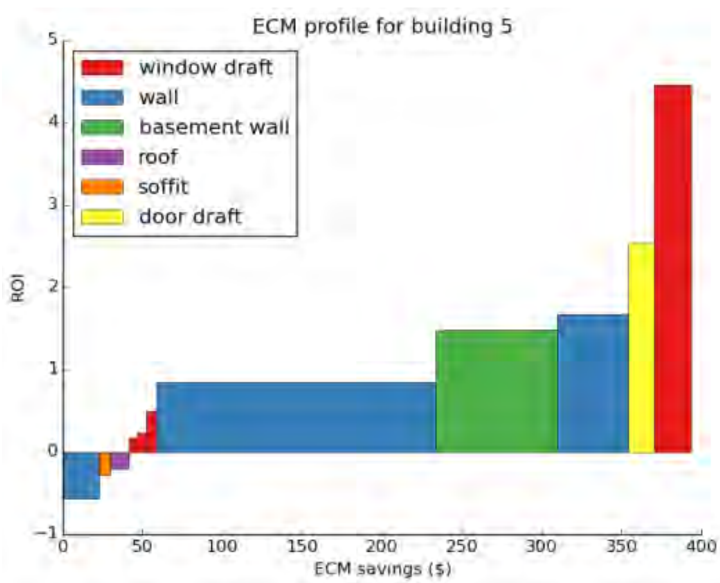


Table 1 lists the recommended envelope ECMs.

Table 1. Envelope ECMs for Bldg 5, Scott AFB.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Improve Wall Insulation	149	358	219	1677	7.6
Basement Wall Insulation	52	124	76	461	6.0
Seal Window Frame Leaks	28	67	41	263	6.4
Seal Door Frame Leaks	11	25	16	66	4.3

Annual potential post-remediation energy savings for this building are $352 and total payback is 7.0 years for envelope-related ECMs.

D.2 Bldg 6

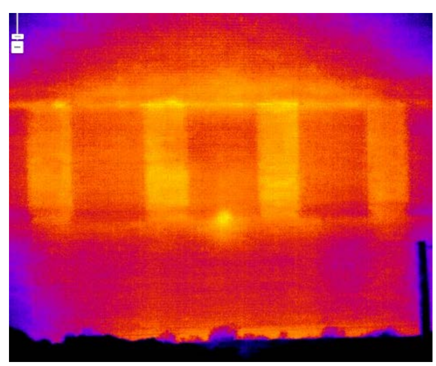
D.2.1 Description of Bldg 6, Scott AFB

Name: Fitness Center
Use Type: Recreation
Square Footage: 25,717
Avg. Daily Electric Use: 1,353.8 kWh
Avg. Daily Gas Use: 42.1 therms
Electricity Score: 60th Percentile
Gas Score: 75th Percentile
Annual Cooling Load: 258,249 kWhrs
Annual Heating Load: 12,995 therms

Bldg 6 (Figures D-6 and D-7) has a relatively high annual gas use (59,738 Btu/sq ft/yr) and roughly average electricity use (19.2 kWh/sq ft/yr) compared to similar buildings on the base.

Figure D-6. Aerial view of Bldg 6, Scott AFB.

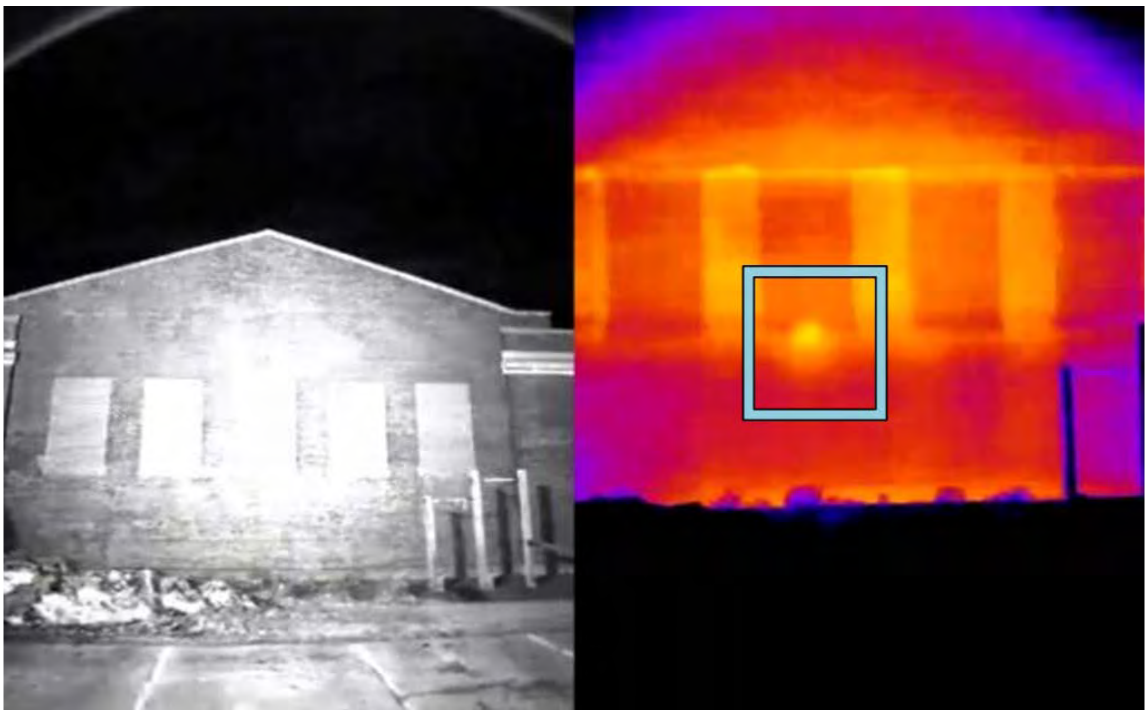
Figure D-7. Thermal image of Bldg 6, Scott AFB.



D.2.2 Notable leaks at Bldg 6, Scott AFB

The wall seen at 65:06 in the Drive-by Application has discernible poorly insulated patches between the bricked-up windows (Figure D-8). There is also a hot spot in the center of the wall, right below the middle bricked-up window. The base manager should check the insulation around the bricked-up windows to prevent some of the energy loss due to poor insulation.

Figure D-8. NIR image (left) and thermal image (right) of Bldg 6, Scott AFB.



D.2.3 Envelope ECMs for Bldg 6, Scott AFB

Figure D-9. Envelope ECM profile for Bldg 6, Scott AFB.

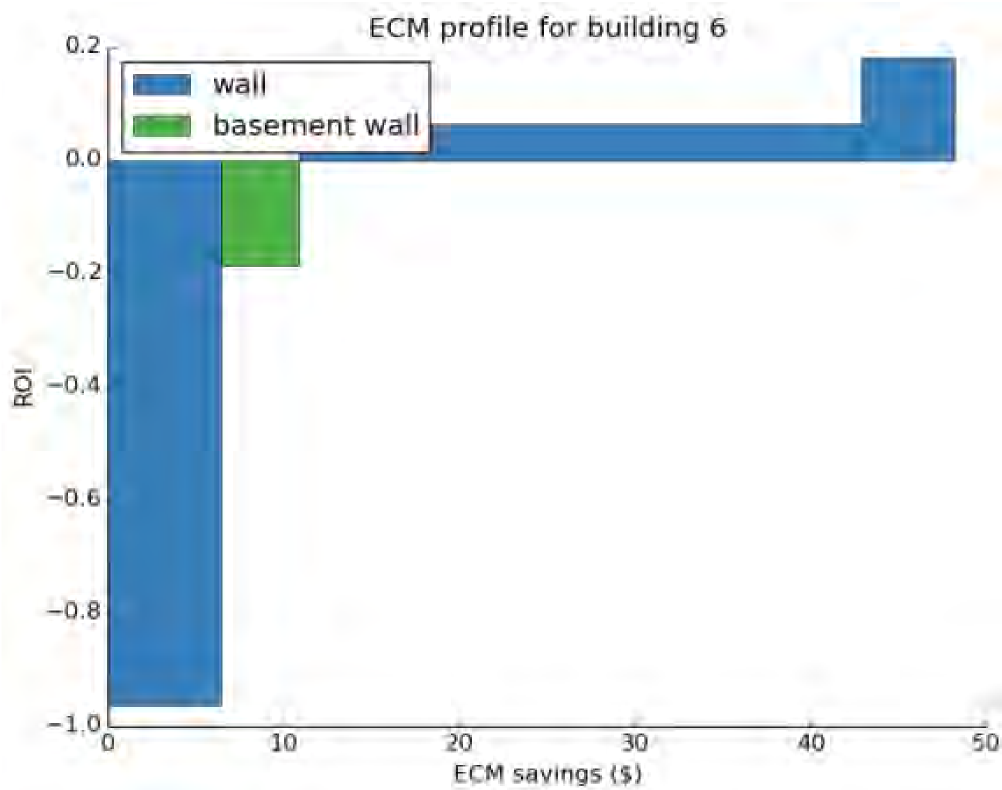


Table 2 lists the recommended envelope ECMs for Bldg 6.

Table 2. Envelope ECMs, Bldg 6, Scott AFB.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Improve Wall Insulation	25	61	37	520	13.9

Annual potential remediation savings for this building are $37 and total payback is 13.9 years for envelope-related ECMs.

D.3 Bldg 8

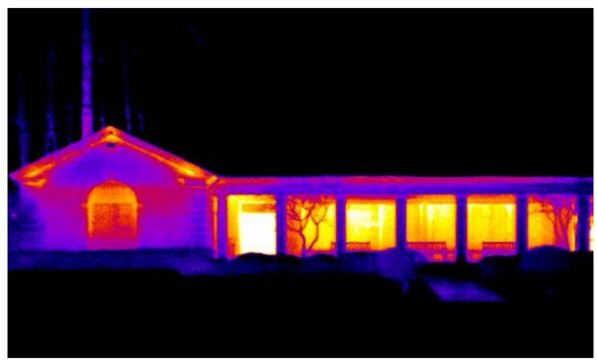
D.3.1 Description of Bldg 8, Scott AFB

Name: Pax Terminal
Use Type: Misc.
Square Footage: 11,169
Avg. Daily Electric Use: 795.7 kWh
Avg. Daily Gas Use: 10.4 therms
Electricity Score: 85th Percentile
Gas Score: 35th Percentile
Annual Cooling Load: 48,735 kWhrs
Annual Heating Load: 3,586 therms

Bldg 8 has a gas usage of 33,872 Btu/sq ft/yr and electricity usage of 26 kWh/sq ft/yr.

Figure D-10. Aerial view of Bldg 8, Scott AFB.

Figure D-11. IR image of Bldg 8, Scott AFB.



D.3.2 Notable leaks at Bldg 8, Scott AFB

The soffit (where the wall meets the roof) at 198:33 in the Drive-by Application is notably emissive (Figure D-12). This should be further investigated.

Figure D-12. NIR image (left) and thermal image (right) of Bldg 8, Scott AFB.

The soffit at 198:44 (Figure D-13) is abnormally emissive. There may be leakage occurring on the wall to the left as well. The area above the door also shows some heat loss, which is most likely caused by poor insulation.

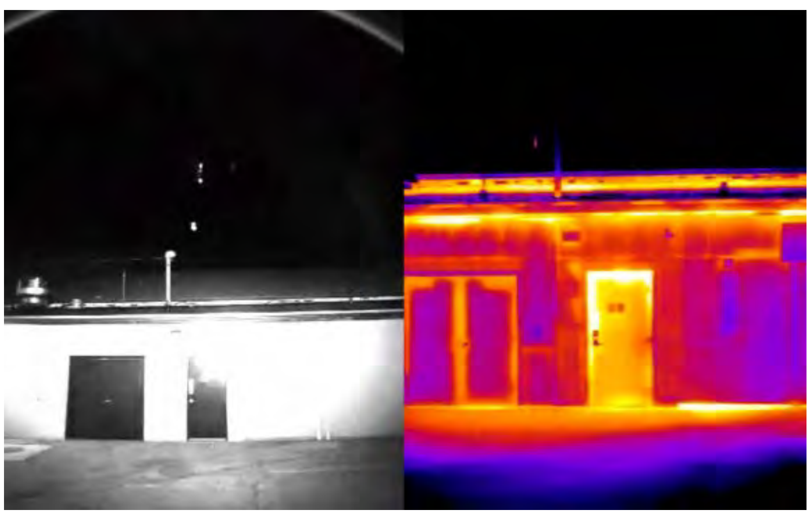
Figure D-13. NIR image (left) and thermal image (right) of Bldg 8, Scott AFB. Note highly emissive area within the rectangle in the right hand image.

Around the back of the building at timestamp 198:53, there are some patches of poorly insulated wall in addition to the leaky soffit (Figure D-14). There may also be a thermal bridge through the insulation represented by the long horizontal line above the window. The immediate fix for this building involves addressing the soffit leaks.

Figure D-14. NIR image (left) and thermal image (right) of Bldg 8, Scott AFB. Areas of the wall and the soffit appear to exhibit high heat loss.

Further along on the same wall, at 198:54, the insulation gaps are even more notable and there is an abnormally emissive door frame (Figure D-15). This may be caused by the door not being closed properly or by a worn out seal around the door.

Figure D-15. NIR image (left) and thermal image (right) of Bldg 8, Scott AFB. The soffit and door frame appear to exhibit high heat loss.



D.3.3 Envelope ECMs for Bldg 8, Scott AFB

Figure D-16 shows the relative ROI for envelope ECMs for Bldg 8, Scott AFB.

Figure D-16. ECM profile for Bldg 8, Scott AFB.

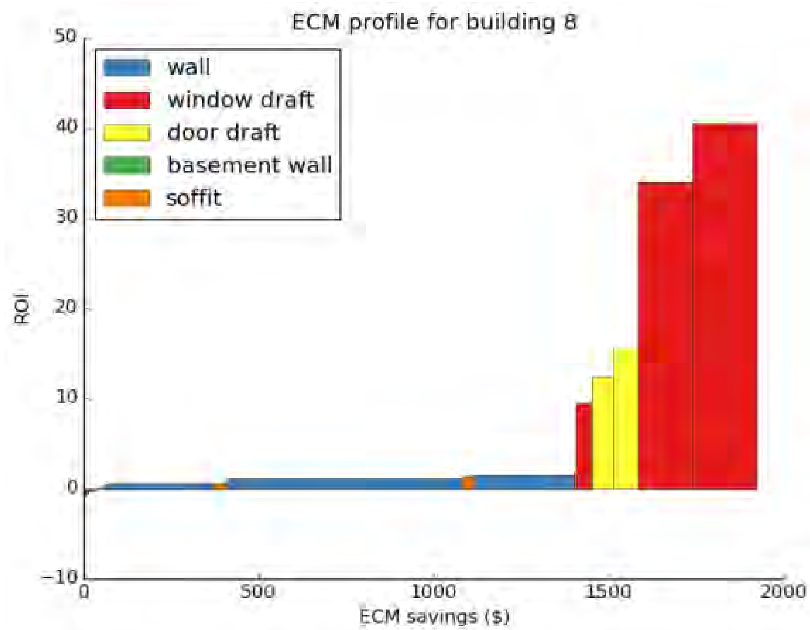


Table 3 lists the recommended envelope ECMs for Bldg 8, Scott AFB.

Table 3. Envelope ECMs for Bldg 8, Scott AFB.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Improve Wall Insulation	852	2052	1258	9529	7.6
Seal Window Frame Leaks	259	623	382	198	0.5
Seal Door Frame Leaks	89	215	132	132	1.0
Improve Soffit Insulation	73	177	108	1043	9.6

Annual potential remediation savings for this building are $1,881 and total payback is 5.8 years for envelope-related ECMs.

D.4 Bldg 10

D.4.1 Description of Bldg 10, Scott AFB

Name: Base Personnel OFC
Use Type: Office
Square Footage: 46,785
Avg. Daily Electric Use: 5,444 kWh
Avg. Daily Gas Use: 38.7 therms
Electricity Score: 95th Percentile
Gas Score: 30th Percentile
Annual Cooling Load: 38,333 kWhrs
Annual Heating Load: 8,947 therms

Bldg 10 (Figures D-17 and D-18) has a gas usage of 30,177 Btu/sq ft/yr and electricity usage of 42.5 kWh/sq ft/yr.

Figure D-17. Aerial view of Bldg 10, Scott AFB.

Figure D-18. Thermal image of Bldg 10, Scott AFB.

D.4.2 Notable leaks at Bldg 10, Scott AFB

There is a particularly emissive patch of wall in the left corner at timestamp 69:25 of the Drive-by Application (Figure D-19). This heat loss captured by the camera system may be caused by poor insulation in the wall. However, this type of signature can also be caused by a piece of equipment generating heat. Given the consistent appearance of the remainder of the building, this area should be further investigated by the base energy manager.

Figure D-19. NIR image (left) and thermal image (right) of Bldg 10, Scott AFB.

D.4.3 Envelope ECMs for Bldg 10, Scott AFB

Figure D-20 shows the relative ROI for envelope ECMs for Bldg 10, Scott AFB.

Figure D-20. ECM profile for Bldg 10, Scott AFB.

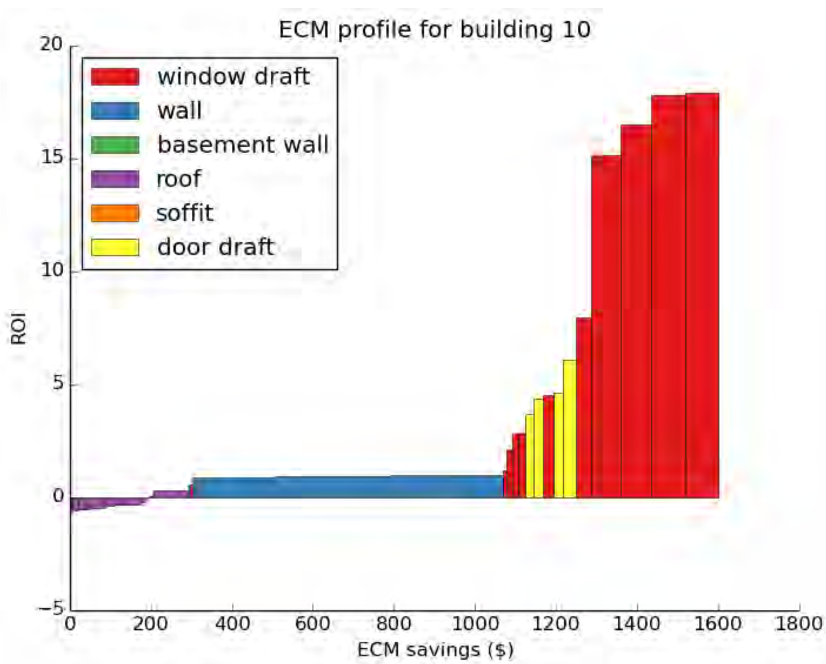


Table D-7 lists the recommended envelope ECMs for Bldg 10, Scott AFB.

Table 4. Envelope ECMs for Bldg 10, Scott AFB.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Improve Wall Insulation	519	1250	767	5967	7.8
Seal Window Frame Leaks	301	725	445	790	1.8
Seal Door Frame Leaks	68	163	100	264	2.6
Improve Roof Insulation	64	154	94	1103	11.7

Annual potential remediation savings for this building are $1,405 and total payback is 5.8 years for envelope-related ECMs.

D.5 Bldg 40

D.5.1 Description of Bldg 40, Scott AFB

Name: Administrative Building
Use Type: Office
Square Footage: 187,909
Avg. Daily Electric Use: Not Provided
Avg. Daily Gas Use: 129 therms
Electricity Score: N/A
Gas Score: 25th Percentile
Annual Cooling Load: N/A
Annual Heating Load: 46,428 therms

Bldg 40 (Figures D-21 and D-22) has a gas usage of 25,044 Btu/sq ft/yr.

Figure D-21. Aerial view of Bldg 40, Scott AFB.

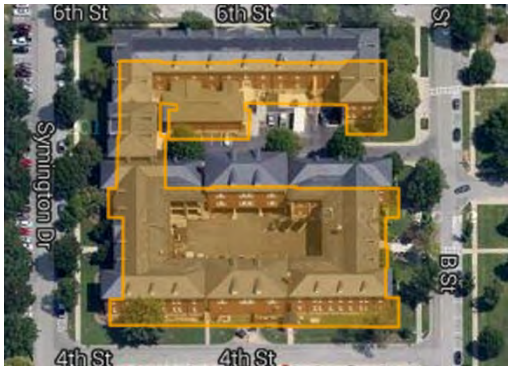
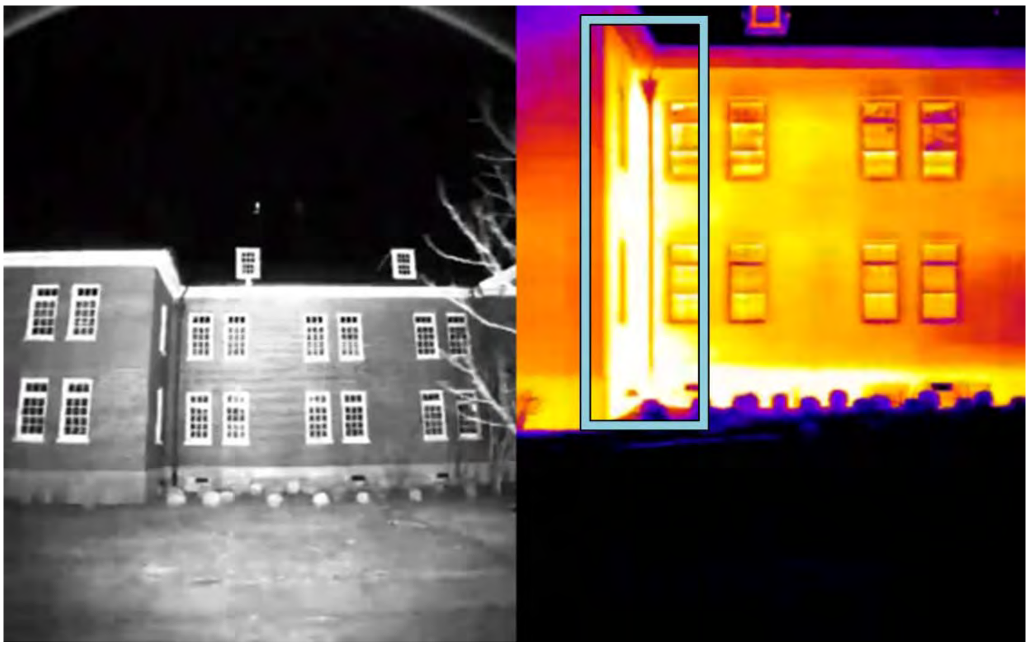


Figure D-22. Thermal image of Bldg 40, Scott AFB.

D.5.2 Notable leaks at Bldg 40, Scott AFB

The corner of the building at 187:20 (Figure D-23) is notably emissive, most likely caused by poor insulation; however, corners can also trap residual solar heat and that effect cannot necessarily be excluded.

Figure D-23. NIR image (left) and thermal image (right) of Bldg 40, Scott AFB.



D.5.3 Envelope ECMs for Bldg 40, Scott AFB

Figure D-24 shows the relative ROI for envelope ECMs for Bldg 40, Scott AFB.

Figure D-24. ECM profile for Bldg 40, Scott AFB.

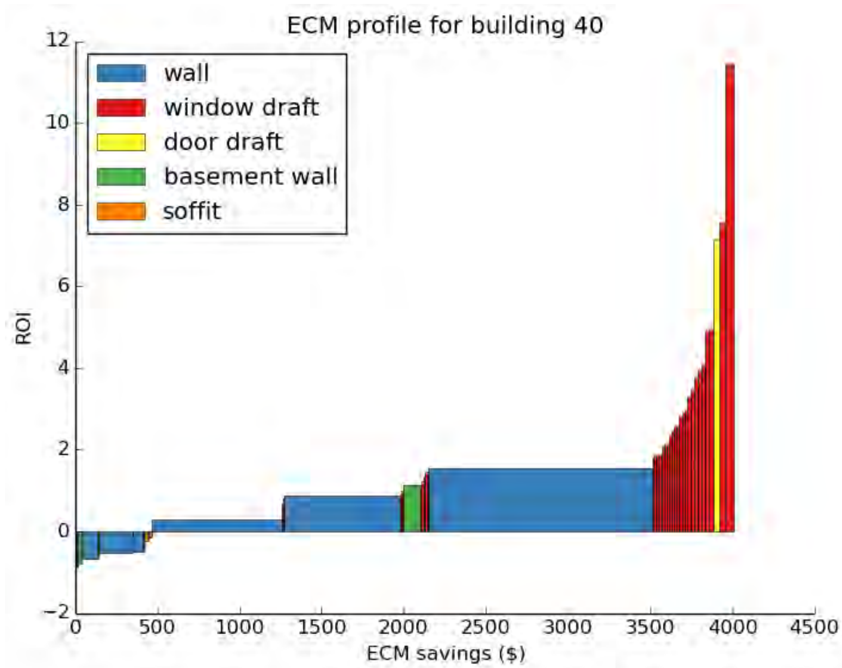


Table 5 lists the recommended envelope ECMs for Bldg 40, Scott AFB.

Table 5. Envelope ECMs for Bldg 40, Scott AFB.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Improve Wall Insulation	1933	4656	2855	22932	8.0
Seal Window Frame Leaks	376	906	555	2237	4.0
Basement Wall Insulation	69	165	101	715	7.1
Seal Door Frame Leaks	24	59	36	66	1.8

Annual potential remediation savings for this building are $3,548 and total payback is 7.3 years for envelope-related ECMs.

D.6 Bldg 61

D.6.1 Description of Bldg 61, Scott AFB

Name: 868 Comm Squadron
Use Type: Office
Square Footage: 17,205
Avg. Daily Electric Use: Not Provided
Avg. Daily Gas Use: 18.2 therms
Electricity Score: N/A
Gas Score: 60th Percentile
Annual Cooling Load: N/A
Annual Heating Load: 5,861 therms

Bldg 61 (Figure D-25 and D-26) has a gas usage of 38,534 Btu/sq ft/yr.

Figure D-25. Aerial view of Bldg 61, Scott AFB.

Figure D-26. Highly emissive areas of Bldg 61, Scott AFB.

D.6.2 Notable leaks at Bldg 61, Scott AFB

The wall surface and door frame around timestamp 71:22 (Figure D-27) are notably emissive. The area of the wall outlined by the rectangle is very poorly insulated.

Figure D-27. NIR image (left) and thermal image (right) of Bldg 61, Scott AFB.

The wall of the attached structure at 71:26 (Figure D-28) is much more emissive than other brick surfaces of the building. In fact, this wall is more emissive than nearly all other emissive brick surfaces across the base. It is likely that the area is missing insulation. There is also a notable insulation hole in the wall at timestamp 71:41, to the left of the electrical box.

Figure D-28. NIR image (left) and thermal image (right) of Bldg 61, Scott AFB. A highly emissive area is shown within the rectangle in the right hand image.

D.6.3 Envelope ECMs for Bldg 61, Scott AFB

Figure D-29 shows the relative ROI for envelope ECMs for Bldg 61, Scott AFB.

Figure D-29. ECM profile for Bldg 61, Scott AFB.

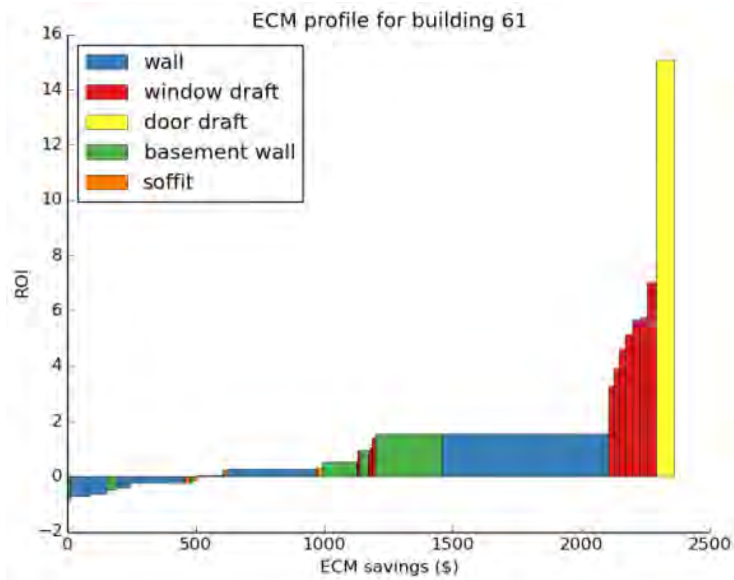


Table 6 lists the recommended envelope ECMs for Bldg 61, Scott AFB.

Table 6. Envelope ECMs for Bldg 61, Scott AFB.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Improve Wall Insulation	672	1615	991	7818	7.9
Basement Wall Insulation	352	848	520	4481	8.6
Seal Window Frame Leaks	155	374	229	790	3.4
Seal Door Frame Leaks	48	115	71	66	0.9
Improve Soffit Insulation	32	76	47	553	11.8

Annual potential remediation savings for this building are $1,858 and total payback is 7.4 years for envelope-related ECMs.

D.7 Bldg 433

D.7.1 Description of Bldg 433, Scott AFB

Name: Sq Ops (Hanger 1)
Use Type: Misc.
Square Footage: 147,405
Avg. Daily Electric Use: Not Provided
Avg. Daily Gas Use: 307.5 therms
Electricity Score: N/A
Gas Score: 90th Percentile
Annual Cooling Load: N/A
Annual Heating Load: 113,075 therms

Bldg 433 (Figures D-30 and D-31) has a gas usage of 76,112 Btu/sq ft/yr.

Figure D-30. Aerial view of Bldg 433, Scott AFB.

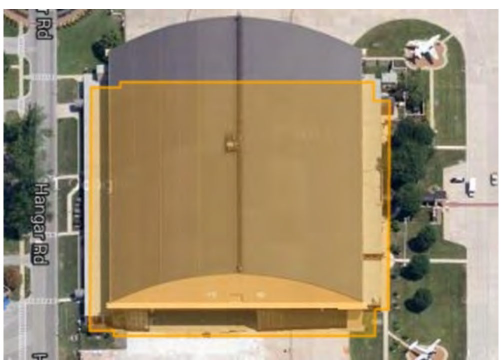
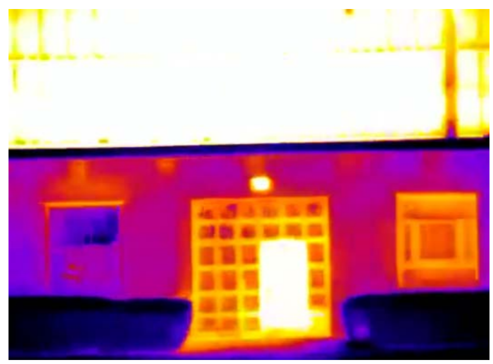


Figure D-31. Thermal image of Bldg 433, Scott AFB.



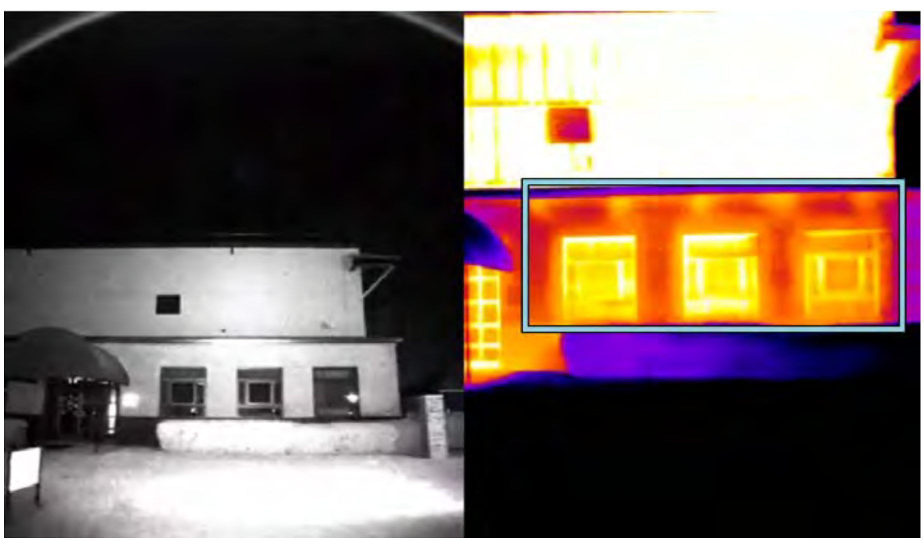
D.7.2 Notable leaks at Bldg 433, Scott AFB

The wall around timestamp 70:13 of the Drive-by Application appears to have reoccurring insulation gaps near the top (Figure D-32). These continue regularly down the length of the wall and can be caused by missing insulation between structural studs.

Figure D-32. NIR image (left) and thermal image (right) of Bldg 433, Scott AFB. A highly emissive area is shown within the rectangle in the right hand image.

These insulation holes also appear around timestamp 70:25 (Figure D-33). Additionally, either the walls around the windows are poorly insulated, or abnormal leakage from the windows is heating the walls around them. This should be investigated as the window leakage issue could be solved with simple weather-stripping and caulking.

Figure D-33. NIR image (left) and thermal image (right) of Bldg 433, Scott AFB. The window frames appear to be highly emissive.



D.7.3 Envelope ECMs for Bldg 433, Scott AFB

Figure D-33 shows the relative ROI for envelope ECMs for Bldg 433, Scott AFB.

Figure D-34. ECM profile for Bldg 433, Scott AFB.

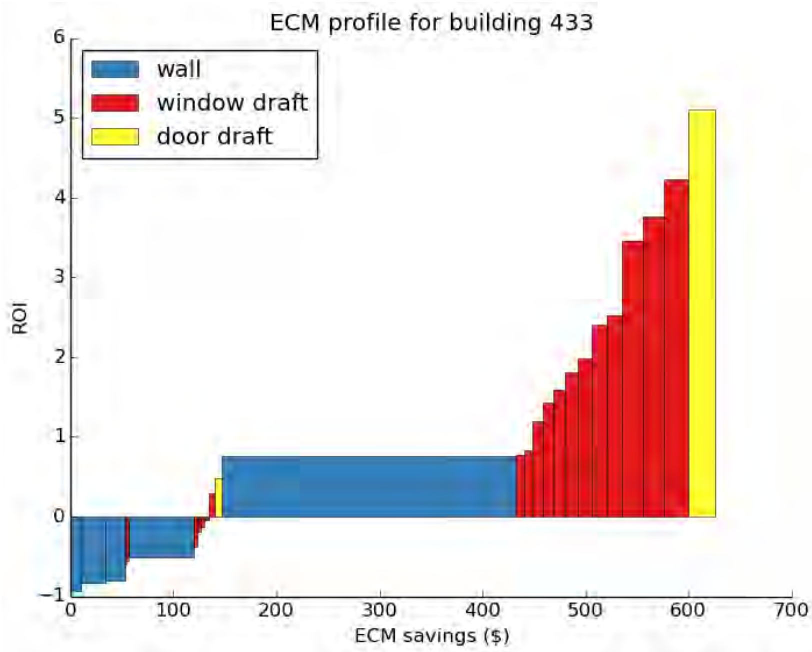


Table 7 lists the recommended envelope ECMs for Bldg 433, Scott AFB.

Table 7. Envelope ECMs for Bldg 433, Scott AFB.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Improve Wall Insulation	194	466	286	2442	8.5
Seal Window Frame Leaks	117	281	172	855	5.0
Seal Door Frame Leaks	23	55	34	133	4.0

Annual potential remediation savings for this building are $492 and total payback is 7.0 years for envelope-related ECMs.

D.8 Bldg 470

D.8.1 Description of Bldg 470, Scott AFB

Name: 932 Squad Ops
Use Type: Office
Square Footage: 39,907
Avg. Daily Electric Use: Not Provided
Avg. Daily Gas Use: 35.4 therms
Electricity Score: N/A
Gas Score: 35th Percentile
Annual Cooling Load: N/A
Annual Heating Load: 9,861 therms

Bldg 470 (Figures D-35 and D-36) has a gas usage of 32,375 Btu/sq ft/yr.

Figure D-35. Aerial view of Bldg 470, Scott AFB.

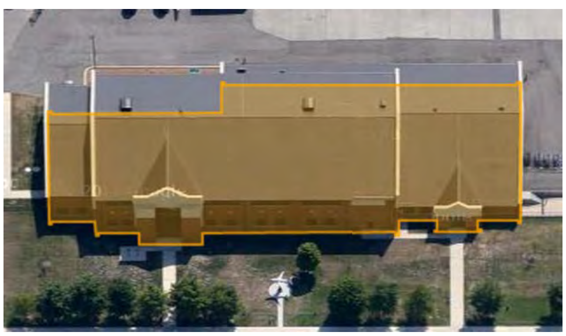
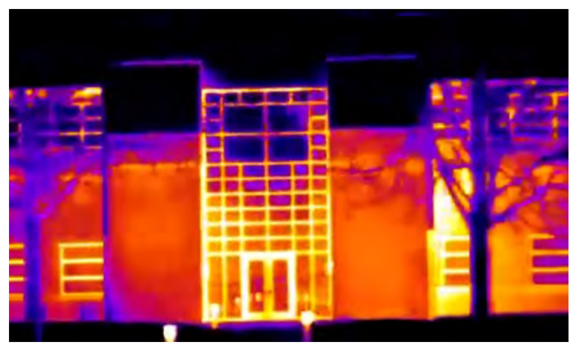


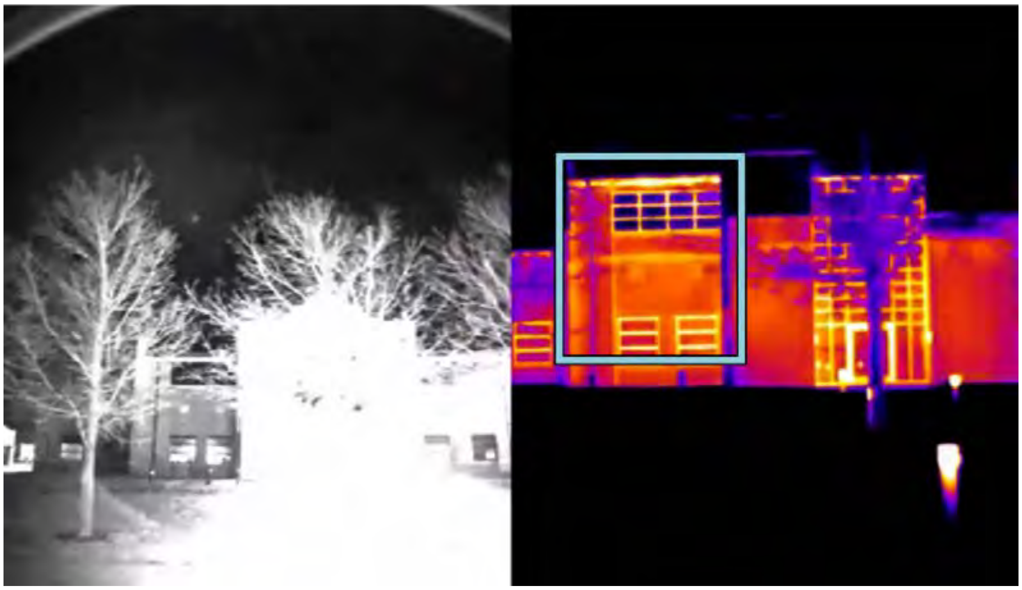
Figure D-36. Thermal image of Bldg 470, Scott AFB.



D.8.2 Notable leaks at Bldg 470, Scott AFB

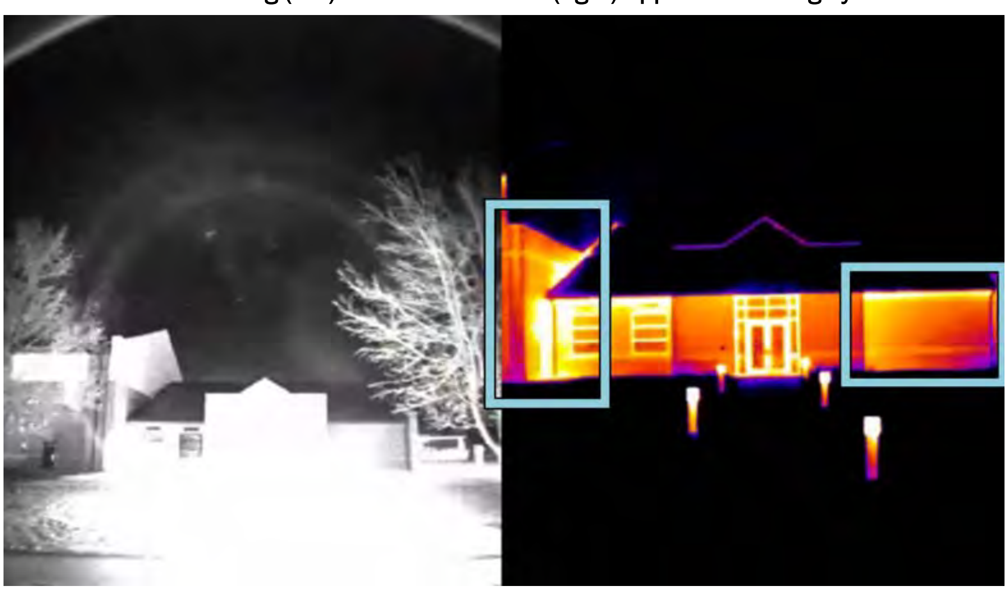
The soffit seen at timestamp 68:29 is fairly emissive (Figure D-37). There are also some spots on the walls that may represent insulation holes and there are soffit leaks across the top portion of the area outlined by the polygon.

Figure D-37. NIR image (left) and thermal image (right) of Bldg 470, Scott AFB.



The soffit on the right side of the image at timestamp 68:36 also appears leaky, and the corner on the left side of the image has several energy leaks (Figure D-38). The leak profile indicates insulation at the joint where the building joins the larger wall (outlined in the left polygon).

Figure D-38. NIR image (left) and thermal image (right) of Bldg 470, Scott AFB. An area in the corner of the building (left) and a wall section (right) appears to be highly emissive.



D.8.3 Envelope ECMs for Bldg 470, Scott AFB

Figure D-39 shows the relative ROI for envelope ECMs for Bldg 470, Scott AFB.

Figure D-39. ECM profile for Bldg 470, Scott AFB.

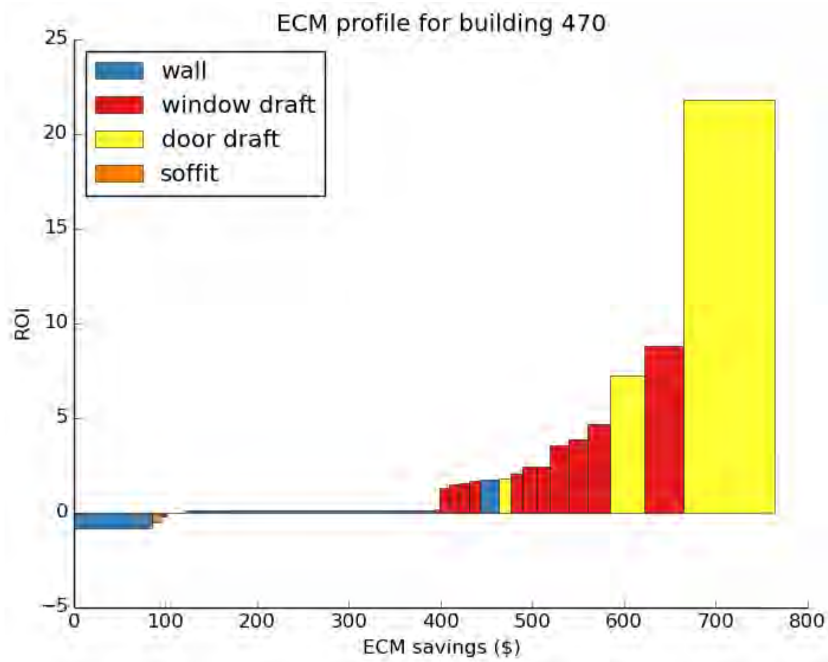


Table 8 lists the recommended envelope ECMs for Bldg 470, Scott AFB.

Table 8. Envelope ECMs for Bldg 470, Scott AFB.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Improve Wall Insulation	198	478	293	3922	13.4
Seal Window Frame Leaks	136	327	200	790	3.9
Seal Door Frame Leaks	101	243	149	199	1.3

Annual potential remediation savings for this building are $643 and total payback is 7.6 years for envelope-related ECMs.

D.9 Bldg 506

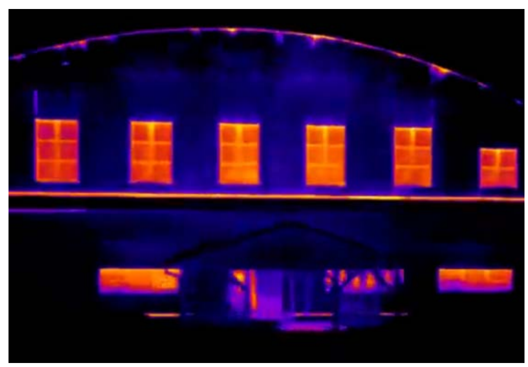
D.9.1 Description of Bldg 506, Scott AFB

Name: Hanger Maintenance
Use Type: Misc.
Square Footage: 34,548
Avg. Daily Electric Use: Not Provided
Avg. Daily Gas Use: 53.9 therms
Electricity Score: N/A
Gas Score: 75th Percentile
Annual Cooling Load: N/A
Annual Heating Load: 19,393 therms

Bldg 506 (Figures D-41 and D-41) has a gas usage of 56,900 Btu/sq ft/yr.

Figure D-40. Aerial view of Bldg 506, Scott AFB.

Figure D-41. Thermal image of Bldg 506, Scott AFB.



D.9.2 Notable leaks at Bldg 506, Scott AFB

The roofline of Bldg 506 is notably warm, as is the door frame to the right of the image at timestamp 235:20 in the Drive-By Tool (Figure D-42).

Figure D-42. NIR image (left) and thermal image (right) of Bldg 506, Scott AFB. A particularly emissive area is shown in the rectangle to the right.

D.9.3 Envelope ECMs for Bldg 506, Scott AFB

Figure D-43 shows the relative ROI for envelope ECMs for Bldg 506, Scott AFB.

Figure D-43. ECM profile for Bldg 506, Scott AFB.

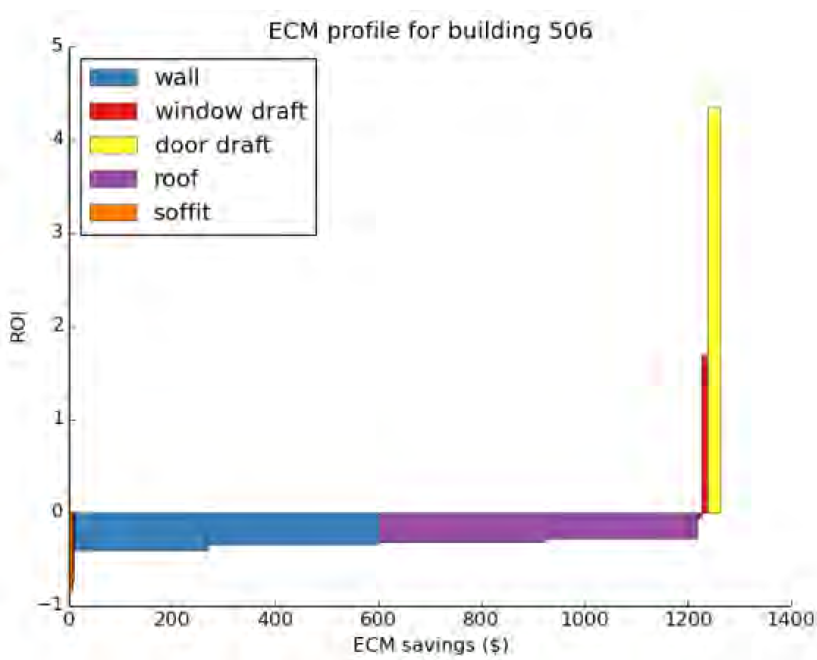


Table 9 lists the recommended envelope ECMs for Bldg 506, Scott AFB.

Table 9. Envelope ECMs for Bldg 506, Scott AFB.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Improve Roof Insulation	417	1005	616	13231	21.5
Improve Wall Insulation	400	967	593	14098	23.8
Seal Door Frame Leaks	16	39	24	66	2.8
Seal Window Frame Leaks	14	33	20	197	9.9

Annual potential remediation savings for this building are $1,253 and total payback is 22 years for envelope-related ECMs.

D.10 Bldg 548

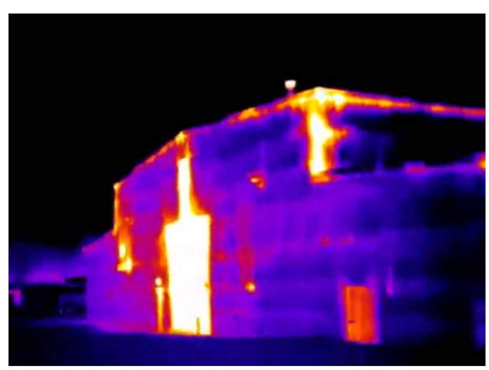
D.10.1 Description of Bldg 548, Scott AFB

Name: Vehicle Maintenance Shop
Use Type: Misc.
Square Footage: 34,793
Avg. Daily Electric Use: 7,334 kWh
Avg. Daily Gas Use: 117.1 therms
Electricity Score: 90th Percentile
Gas Score: 95th Percentile
Annual Cooling Load: 131,125 kWhrs
Annual Heating Load: 39,990 therms

Bldg 548 (Figures D-44 and D-45) has a gas usage of 122,769 Btu/sq ft/yr and electricity usage of 76.9 kWh/sq ft/yr.

Figure D-44. Aerial view of Bldg 548, Scott AFB.

Figure D-45. Thermal image of Bldg 548, Scott AFB.



D.10.2 Notable leaks at Bldg 548, Scott AFB

The wall surface at timestamp 75:36 (Figure D-46) has some large, highly emissive patches to the left of the large garage door. The corner of the wall shown in the middle of the image also seems to be poorly insulated.

Figure D-46. NIR image (left) and thermal image (right) of Bldg 548, Scott AFB. The large door, upper corner and soffit areas appear to be thermally inefficient.

The soffit at the top of the wall at timestamp 75:37 (Figure D-47) is highly emissive. The garage doors themselves are emitting a lot of heat, though this may be difficult to effectively remediate.

Figure D-47. NIR image (left) and thermal image (right) of Bldg 548, Scott AFB. The garage doors and soffit areas appear to be thermally inefficient.

D.10.3 Envelope ECMs for Bldg 548, Scott AFB

Figure D-48 shows the relative ROI for envelope ECMs for Bldg 548, Scott AFB.

Figure D-48. ECM profile for Bldg 548, Scott AFB.

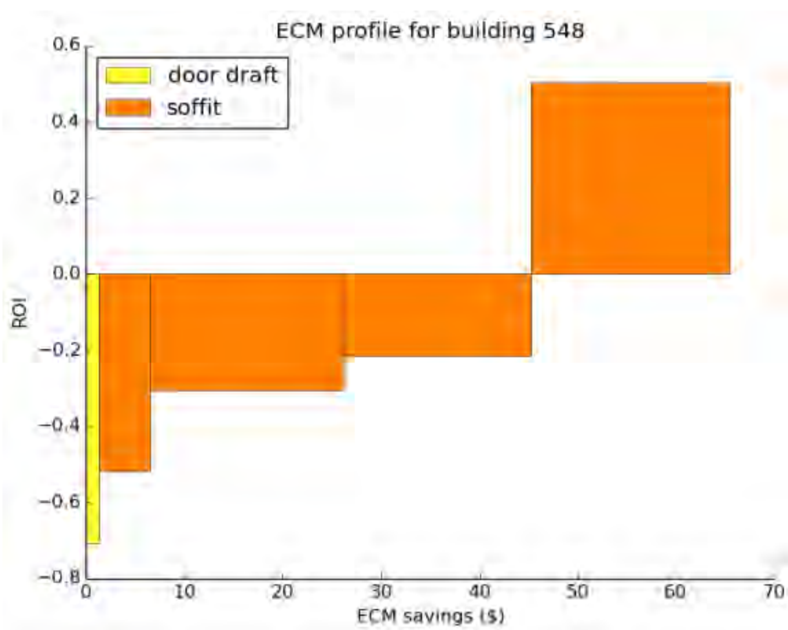


Table 10 lists the recommended envelope ECMs for Bldg 548, Scott AFB.

Table 10. Envelope ECMs for Bldg 548, Scott AFB.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Improve Soffit Insulation	14	33	20	202	10.0

Annual potential remediation savings for this building are $20 and total payback is 10 years for envelope-related ECMs.

D.11 Bldg 700

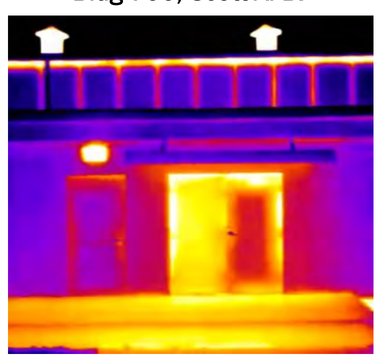
D.11.1 Description of Bldg 700, Scott AFB

Name: Visual Info Service Center
Use Type: Office
Square Footage: 51,782
Avg. Daily Electric Use: 1,016 kWh
Avg. Daily Gas Use: Not Provided
Electricity Score: 35th Percentile
Gas Score: N/A
Annual Cooling Load: N/A
Annual Heating Load: N/A

Bldg 700 (Figures D-49 and D-50) has an electricity usage of 7.1 kWh/sq ft/yr.

Figure D-49. Aerial view of Bldg 700, Scott AFB.

Figure D-50. Thermal image of Bldg 700, Scott AFB.



D.11.2 Notable leaks at Bldg 700, Scott AFB

Figure D-51 shows a patch of wall that appears to have poor insulation relative to the surrounding wall at timestamp 229:04.

Figure D-51. NIR image (left) and thermal image (right) of Bldg 700, Scott AFB. This wall section appears to be highly emissive.

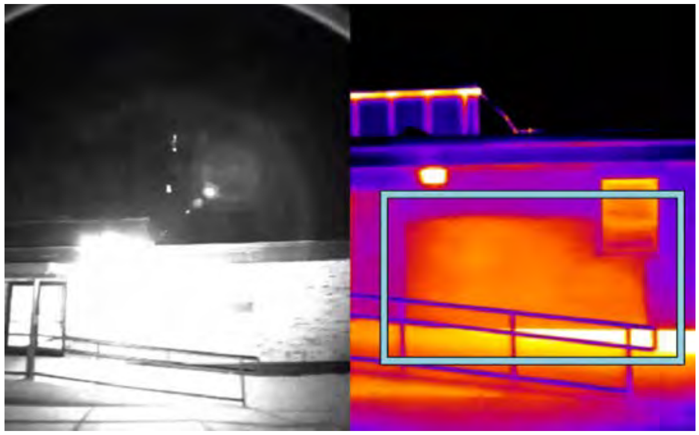


Figure D-52 shows another similar patch of poorly insulated wall shows up at timestamp 229:06.

Figure D-52. NIR image (left) and thermal image (right) of Bldg 700, Scott AFB. Another wall section appears to be highly emissive.

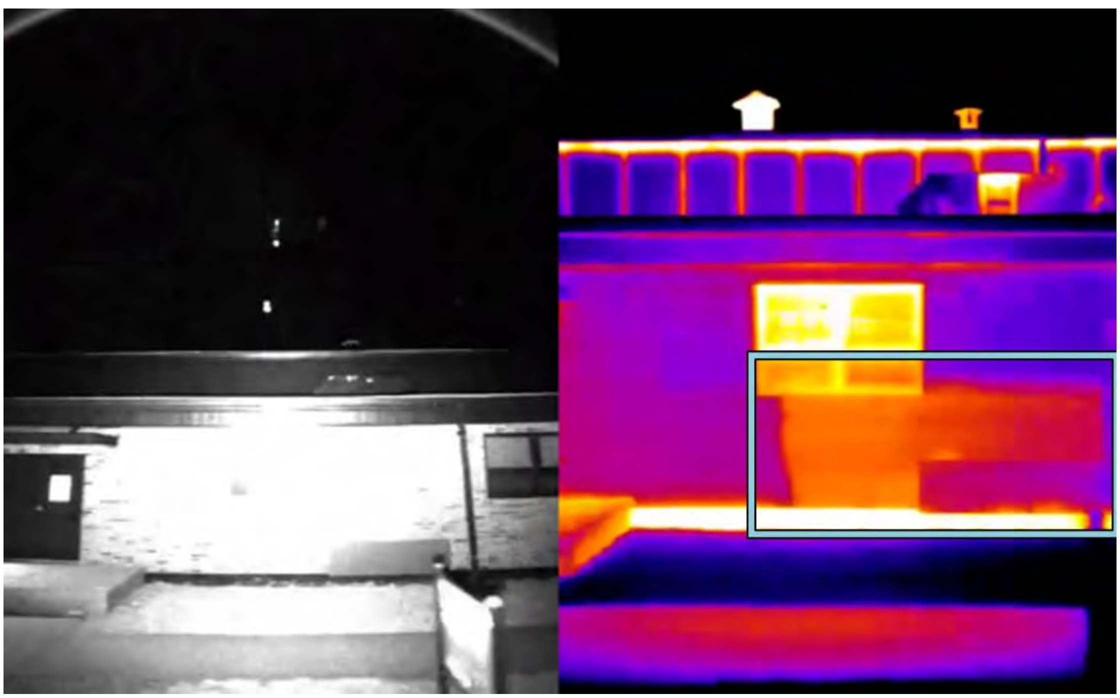


Figure D-53 shows that the door at timestamp 229:07 has a highly emissive frame, and that the left part of the door seems to be much more poorly insulated in general than the right.

Figure D-53. NIR image (left) and thermal image (right) of Bldg 700, Scott AFB. The door frame and door panel appear to be highly emissive.

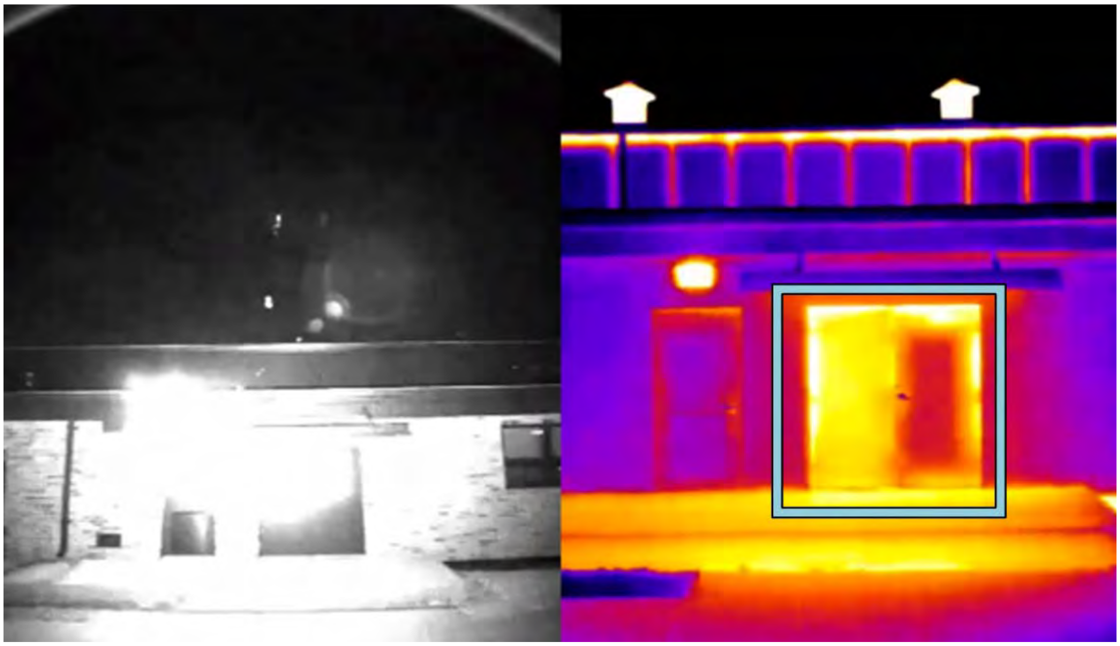
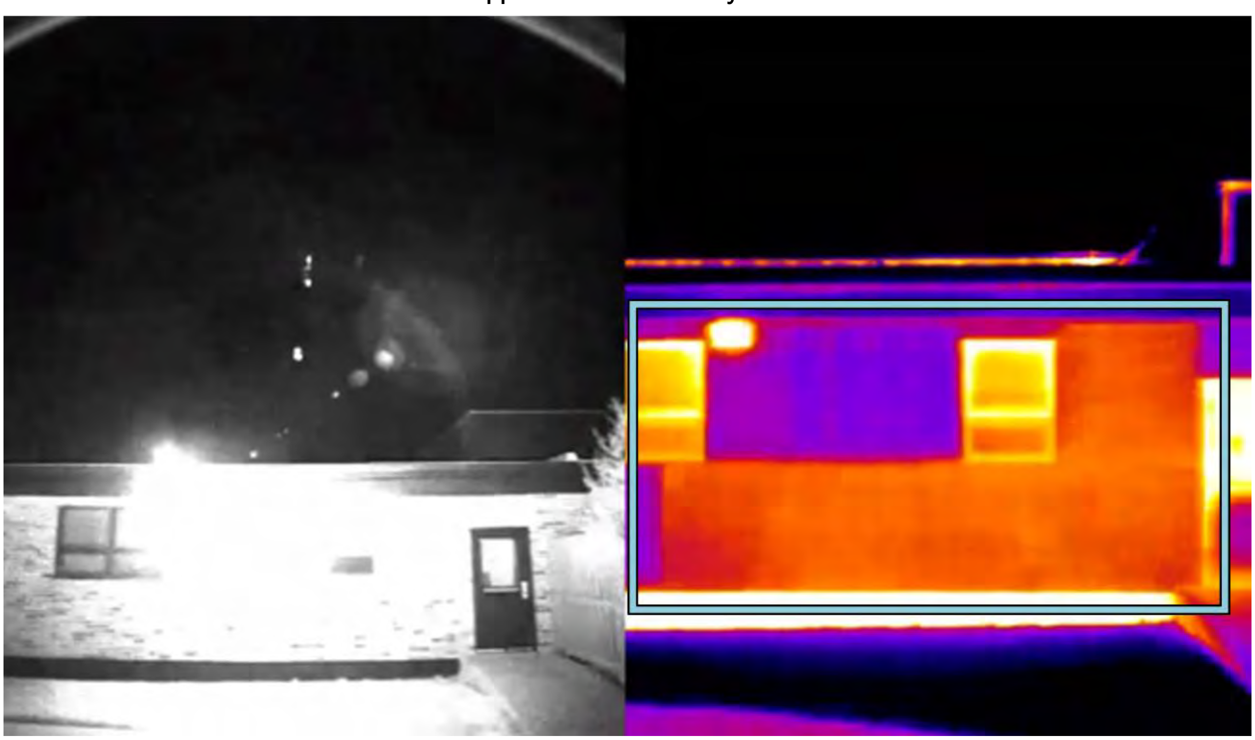


Figure D-54 shows another large patch of relatively poorly insulated wall visible at timestamp 229:12, which is particularly noticeable when compared to the area between the two windows.

Figure D-54. NIR image (left) and thermal image (right) of Bldg 700, Scott AFB. This wall section appears to be thermally inefficient.



D.11.3 Envelope ECMs for Bldg 700, Scott AFB

Figure D-55 shows the relative ROI for envelope ECMs for Bldg 700, Scott AFB.

Figure D-55. ECM profile for Bldg 700, Scott AFB.

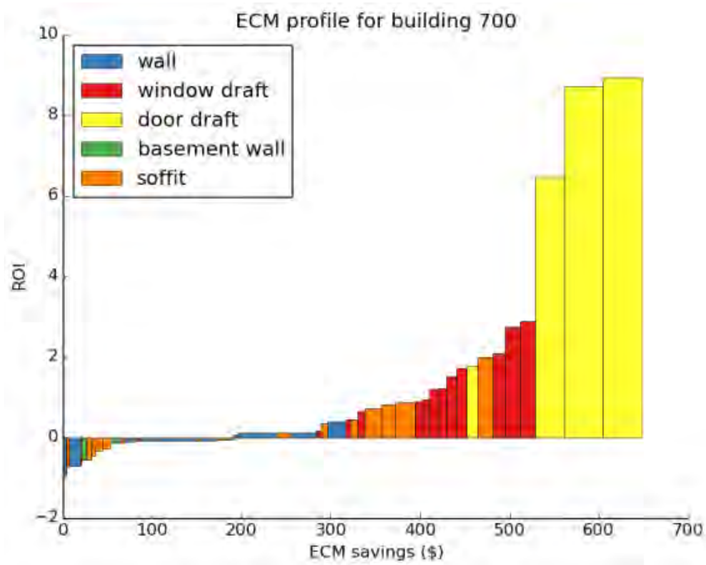


Table 11 lists the recommended envelope ECMs for Bldg 700, Scott AFB.

Table 11. Envelope ECMs for Bldg 700, Scott AFB.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Seal Door Frame Leaks	89	214	131	264	2.0
Seal Window Frame Leaks	87	210	129	854	6.6
Improve Soffit Insulation	70	170	104	927	8.9
Improve Wall Insulation	63	151	93	1199	12.9

Annual potential remediation savings for this building are $457 and total payback is 7.1 years for envelope-related ECMs.

D.12 Bldg 755

D.12.1 Description of Bldg 755, Scott AFB

Name: Security Forces
Use Type: Office
Square Footage: 35,900
Avg. Daily Electric Use: Not Provided
Avg. Daily Gas Use: 39.8 therms
Electricity Score: N/A
Gas Score: 60th Percentile
Annual Cooling Load: N/A
Annual Heating Load: 10,087 therms
Gas Usage: 40,442 Btu/sq ft/yr.

Bldg 755 (Figures D-56 and D-57) has a gas usage of 40,442 Btu per square foot per year.

Figure D-56. Aerial view of Bldg 755, Scott AFB.

Figure D-57. IR image of Bldg 755, Scott AFB.

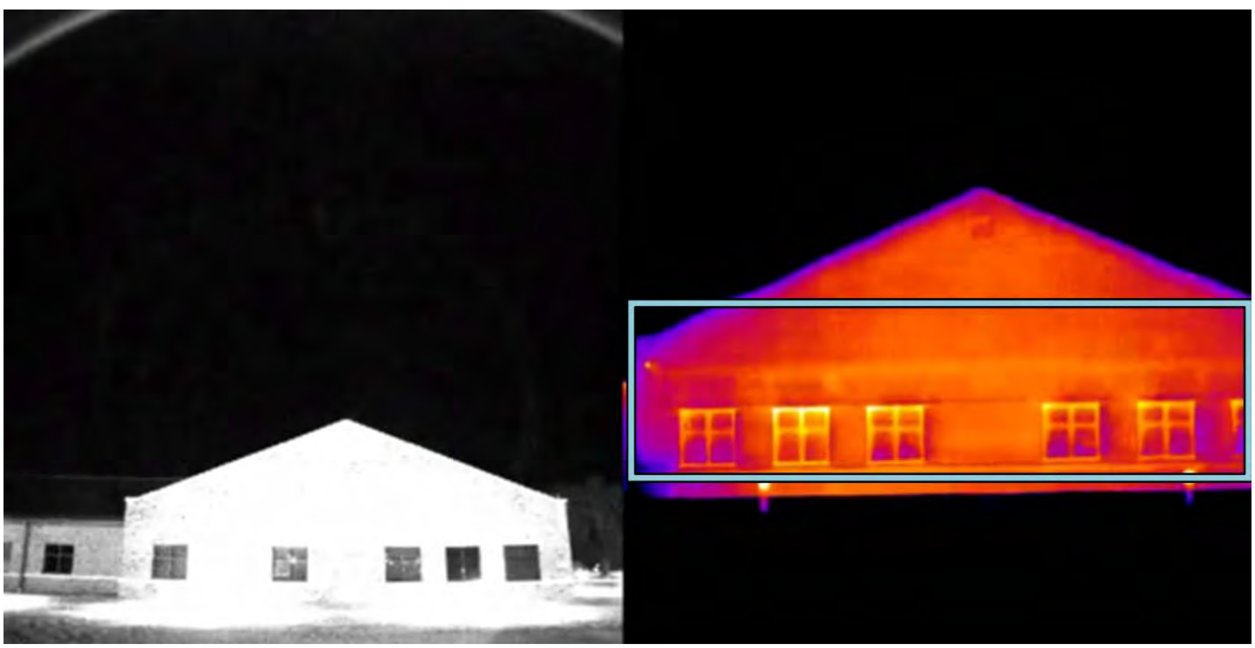
D.12.2 Notable leaks at Bldg 755, Scott AFB

There is a suspicious hotspot in the corner of the wall around timestamp 89:07 that may indicate a poorly insulated location (Figure D-58).

Figure D-58. NIR image (left) and thermal image (right) of Bldg 755, Scott AFB. A particularly emissive area is in the rectangle at the right.

The wall at timestamp 89:18 is fairly emissive, and there is a horizontal thermal bridge visible above the windows (Figure D-59).

Figure D-59. NIR image (left) and thermal image (right) of Bldg 755, Scott AFB.



The wall around timestamp 89:34 is also highly emissive, with particular bright spots along window frames in the middle of the image (Figure D-60).

Figure D-60. NIR image (left) and thermal image (right) of Bldg 755, Scott AFB. The window frames appear to be particularly emissive.

D.12.3 Envelope ECMs for Bldg 755, Scott AFB

Figure D-61 shows the relative ROI for envelope ECMs for Bldg 700, Scott AFB.

Figure D-61. ECM profile for Bldg 755, Scott AFB.

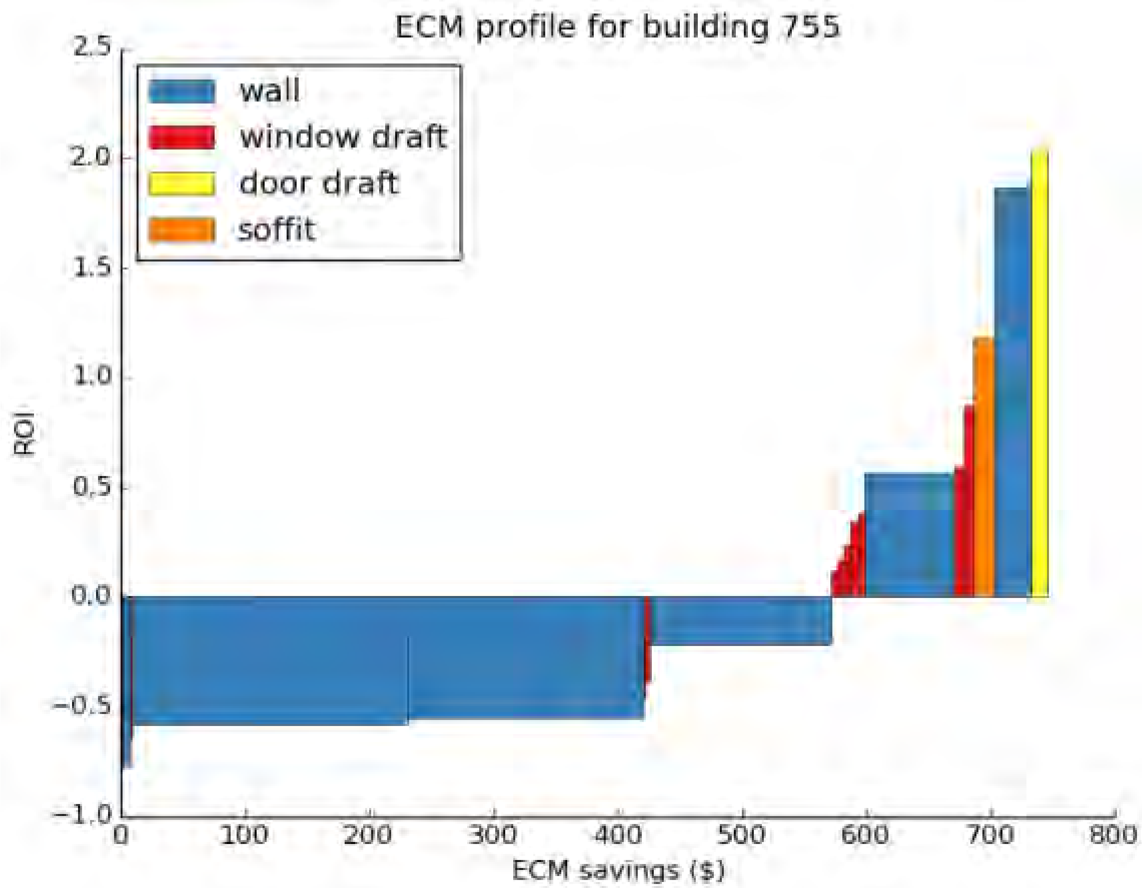


Table 12 lists the recommended envelope ECMs for Bldg 755, Scott AFB.

Table 12. Envelope ECMs for Bldg 755, Scott AFB.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Improve Wall Insulation	69	166	102	847	8.3
Seal Window Frame Leaks	29	69	43	460	10.8
Improve Soffit Insulation	11	27	16	112	6.9
Seal Door Frame Leaks	9	22	13	66	5.0

Annual potential remediation savings for this building are $174 and total payback is 8.5 years for envelope-related ECMs.

D.13 Bldg 861

D.13.1 Description of Bldg 861, Scott AFB

Name: HQ AMC/CSS
Use Type: Office
Square Footage: 42,529
Avg. Daily Electric Use: 1,108 kWh
Avg. Daily Gas Use: 21 therms
Electricity Score: 45th Percentile
Gas Score: 10th Percentile
Annual Cooling Load: 162,979 kWhrs
Annual Heating Load: 9,068 therms

Bldg 861 (Figures E-62 and E-63) has a gas usage of 18,011 Btu/sq ft/yr and electricity usage of 9.5 kWh/sq ft/yr.

Figure D-62. Aerial view of Bldg 861, Scott AFB.

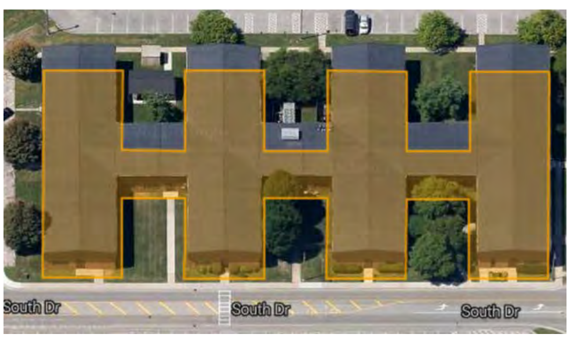
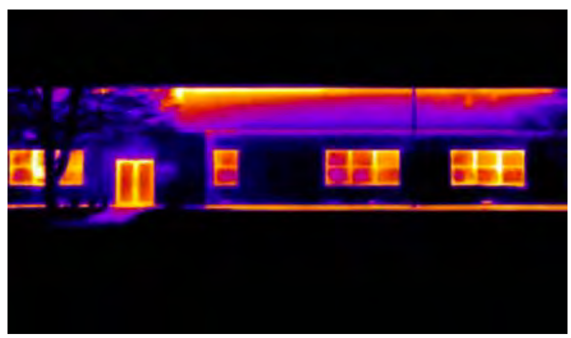


Figure D-63. Thermal image of Bldg 861, Scott AFB.



D.13.2 Notable leaks at Bldg 861, Scott AFB

The roof at timestamp 223:10 is losing significant energy when compared to the rest of the building (Figure D-64).

Figure D-64. NIR image (left) and thermal image (right) of Bldg 861, Scott AFB. Significant heat loss appears to be shown at the roof line.

The roof at timestamp 223:25 is also notably emissive while the rest of the building is not particularly emissive (Figure D-65).

Figure D-65. NIR image (left) and thermal image (right) of Bldg 861, Scott AFB. Another view of apparent heat loss at the roof line.

D.13.3 Envelope ECMs for Bldg 861, Scott AFB

Figure D-66 shows the relative ROI for envelope ECMs for Bldg 861, Scott AFB.

Figure D-66. ECM profile for Bldg 861, Scott AFB.

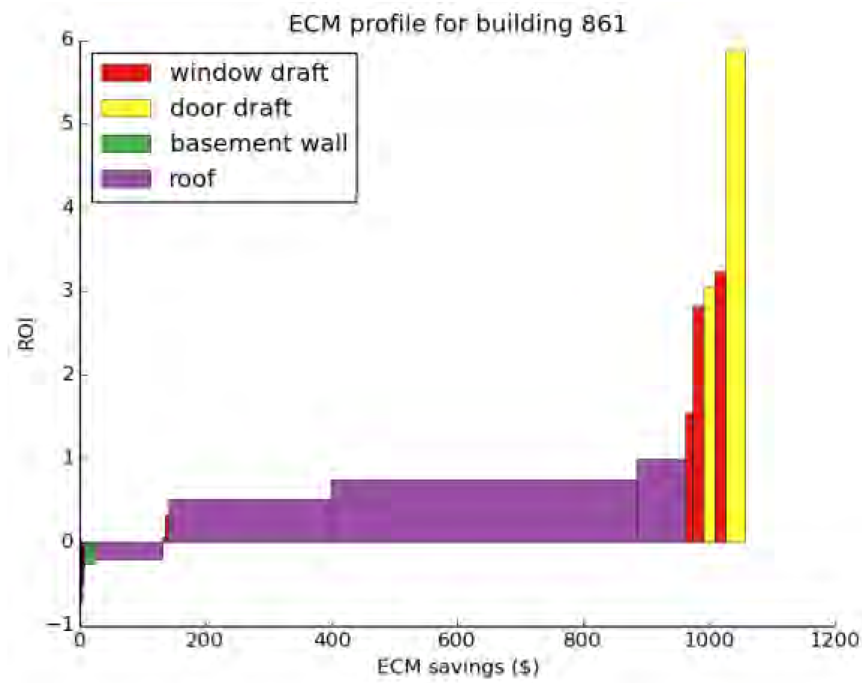


Table 13 lists the recommended envelope ECMs for Bldg 861, Scott AFB.

Table 13. Envelope ECMs for Bldg 861, Scott AFB.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Improve Roof Insulation	555	1337	820	7314	8.9
Seal Window Frame Leaks	39	93	57	331	5.8
Seal Door Frame Leaks	33	78	48	132	2.8

Annual potential remediation savings for this building are $925 and total payback is 8.4 years for envelope-related ECMs.

D.14 Bldg 1512

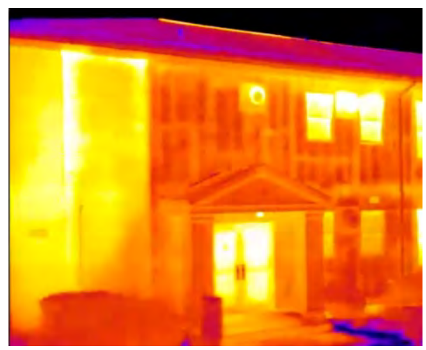
D.14.1 Description of Bldg 1512, Scott AFB

Name: Dorm VOQ
Use Type: Multifamily
Square Footage: 22,932
Avg. Daily Electric Use: Not Provided
Avg. Daily Gas Use: 24.1 therms
Electricity Score: N/A
Gas Score: 35th Percentile
Annual Cooling Load: N/A
Annual Heating Load: 6,147 therms

Bldg 1512 (Figures D-67 and D-68) has a gas usage of 38,288 Btu/sq ft/yr.

Figure D-67. Aerial view of Bldg 1512, Scott AFB.

Figure D-68. Thermal image of Bldg 1512, Scott AFB.



D.14.2 Notable leaks at Bldg 1512, Scott AFB

There are notable insulation gaps and thermal bridges along the surface of the wall at timestamp 134:08 (Figure D-69). The entire wall is poorly insulated. The area above the second floor windows also appears to be lacking insulation.

Figure D-69. NIR image (left) and thermal image (right) of Bldg 1512, Scott AFB. The doors and windows appear to be highly emissive.

D.14.3 Envelope ECMs for Bldg 1512, Scott AFB

Figure D-70 shows the relative ROI for envelope ECMs for Bldg 1512, Scott AFB.

Figure D-70. ECM profile for Bldg 1512, Scott AFB.

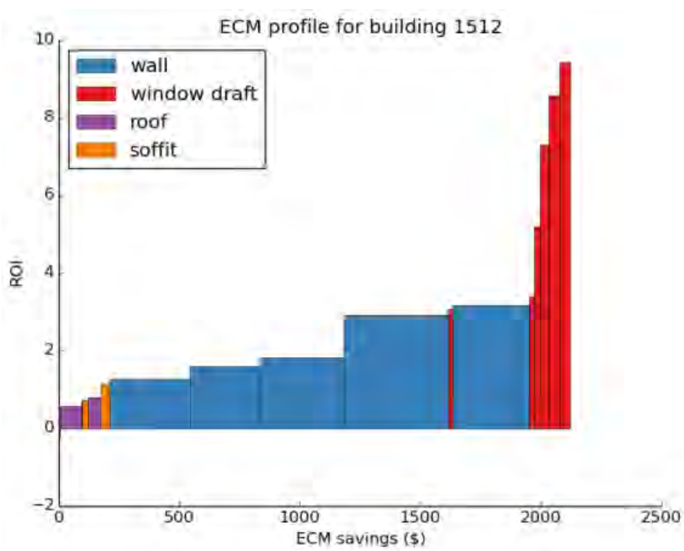


Table 14 lists the recommended Envelope ECMs for Bldg 1512, Scott AFB.

Table 14. Envelope ECMs for Bldg 1512, Scott AFB.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Improve Wall Insulation	1166	2807	1721	8546	5.0
Seal Window Frame Leaks	132	318	195	460	2.4
Improve Roof Insulation	96	232	142	1295	9.1
Improve Soffit Insulation	40	96	59	448	7.6

Annual potential remediation savings for this building are $2,117 and total payback is 5.1 years for envelope-related ECMs.

D.15 Bldg 1521

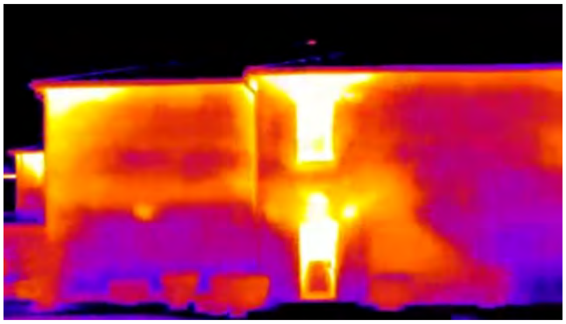
D.15.1 Description of Bldg 1521, Scott AFB

Name: HQ AMC
Use Type: Office
Square Footage: 51,315
Avg. Daily Electric Use: Not Provided
Avg. Daily Gas Use: 73.8 therms
Electricity Score: N/A
Gas Score: 70th Percentile
Annual Cooling Load: N/A
Annual Heating Load: 12,752 therms

Bldg 1521 (Figures D-71 and D-72) was imaged early in the evening, and while the walls appear highly emissive in thermal images much of this is likely due to residual solar heat. Once the surface temperature has been normalized for observation time, mitigation potential from insulation improvements is relatively small. Bldg 1521 has a gas usage of 52,465 Btu/sq ft/yr.

Figure D-71. Aerial view of Bldg 1521, Scott AFB.

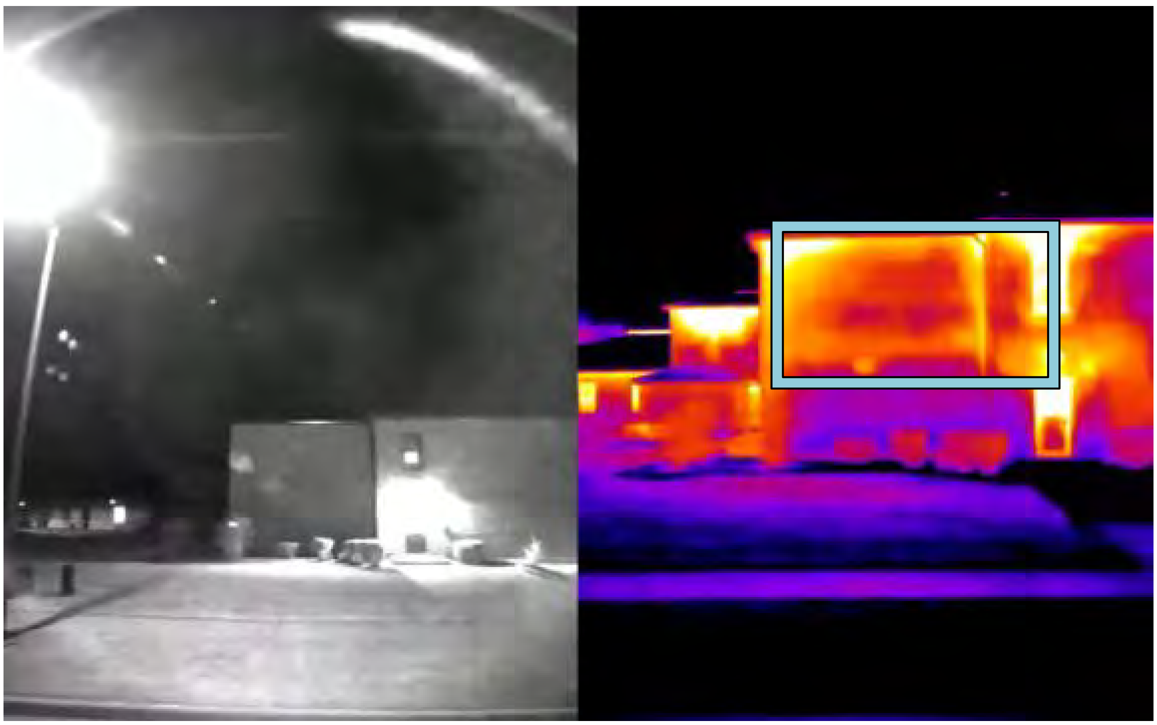
Figure D-72. Thermal image of Bldg 1521, Scott AFB.



D.15.2 Notable leaks at Bldg 1521, Scott AFB

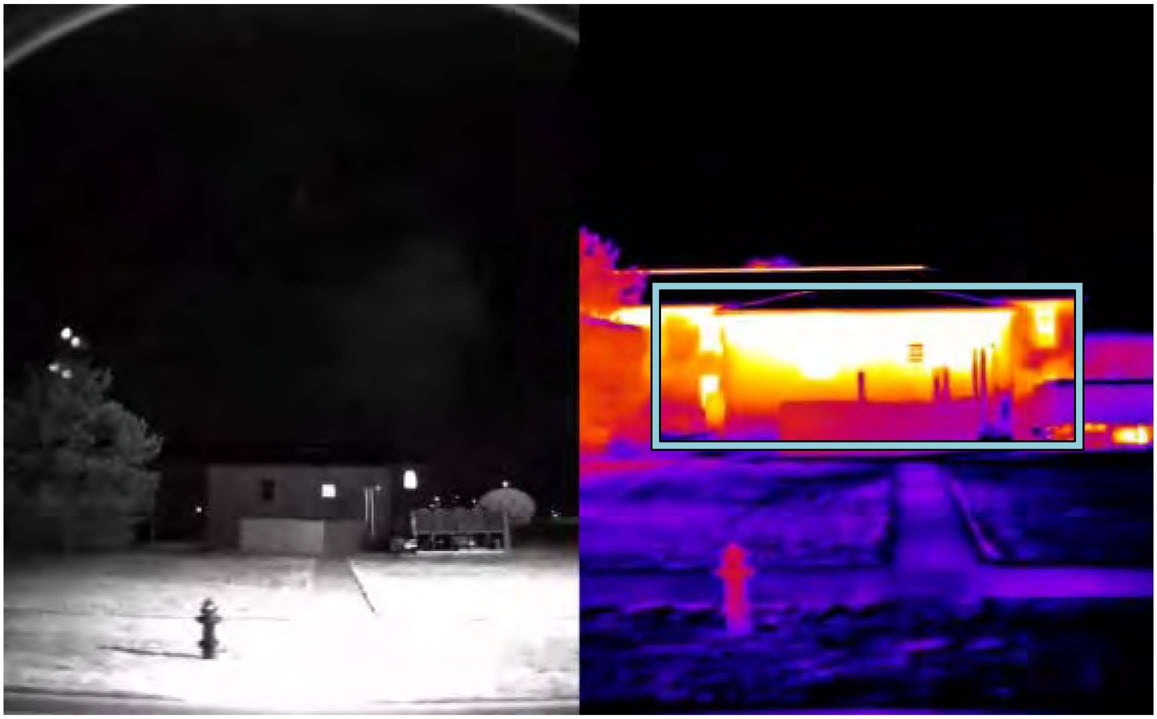
The wall near the beginning of the drive-by video for Bldg 1521 shows highly emissive portions of the brick wall, which indicates poor insulation (Figure D-73). As seen in other buildings, there is heat loss on top of both windows.

Figure D-73. NIR image (left) and thermal image (right) of Bldg 1521, Scott AFB. A highly emissive wall section is shown in the box to the right.



Near the end of the building video there is a highly emissive wall, which also indicates poor insulation (Figure D-74).

Figure D-74. NIR image (left) AND thermal image (right) of Bldg 1521, Scott AFB.



D.15.3 Envelope ECMs for Bldg 1521, Scott AFB

Figure D-75 shows the relative ROI for envelope ECMs for Bldg 1521, Scott AFB.

Figure D-75. ECM profile for Bldg 1521, Scott AFB.

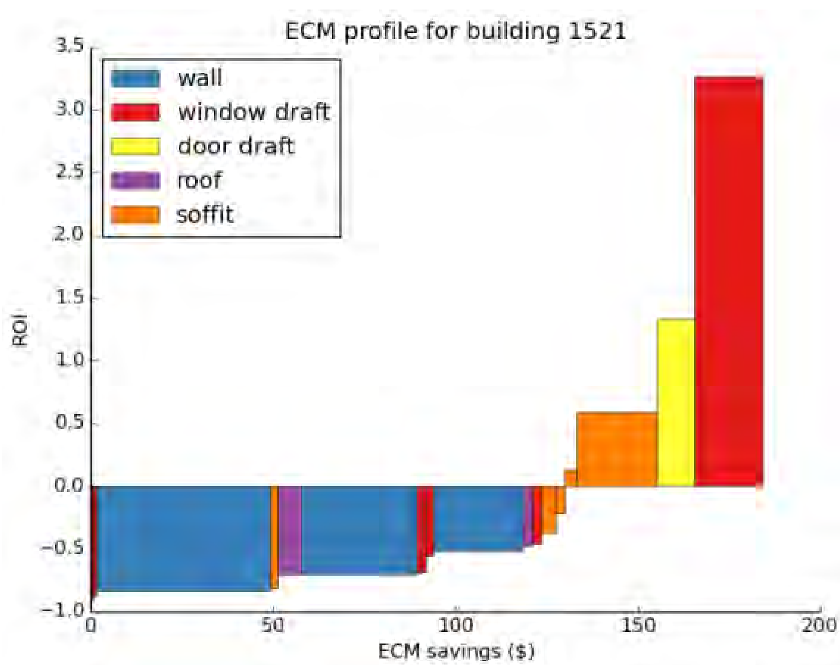


Table 15 lists the recommended envelope ECMs for Bldg 1521, Scott AFB.

Table 15. Envelope ECMs for Bldg 1521, Scott AFB.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Improve Soffit Insulation	17	41	25	251	9.9
Seal Window Frame Leaks	13	30	19	65	3.5
Seal Door Frame Leaks	7	17	10	67	6.4

Annual potential remediation savings for this building are $54 and total payback is 7.1 years for envelope-related ECMs.

D.16 Bldg 1529

D.16.1 Description of Bldg 1529, Scott AFB

Name: Aeromed Stg Fclty
Use Type: Misc
Square Footage: 34,028
Avg. Daily Electric Use: 4,694 kWh
Avg. Daily Gas Use: 1.4 therms
Electricity Score: 100th Percentile
Gas Score: 0th Percentile
Annual Cooling Load: 910,825 kWhrs
Annual Heating Load: 487 therms

Bldg 1529 (Figures D-76 and D-77) has a gas usage of 1,509 Btu/sq ft/yr and electricity usage of 50.3 kWh/sq ft/yr.

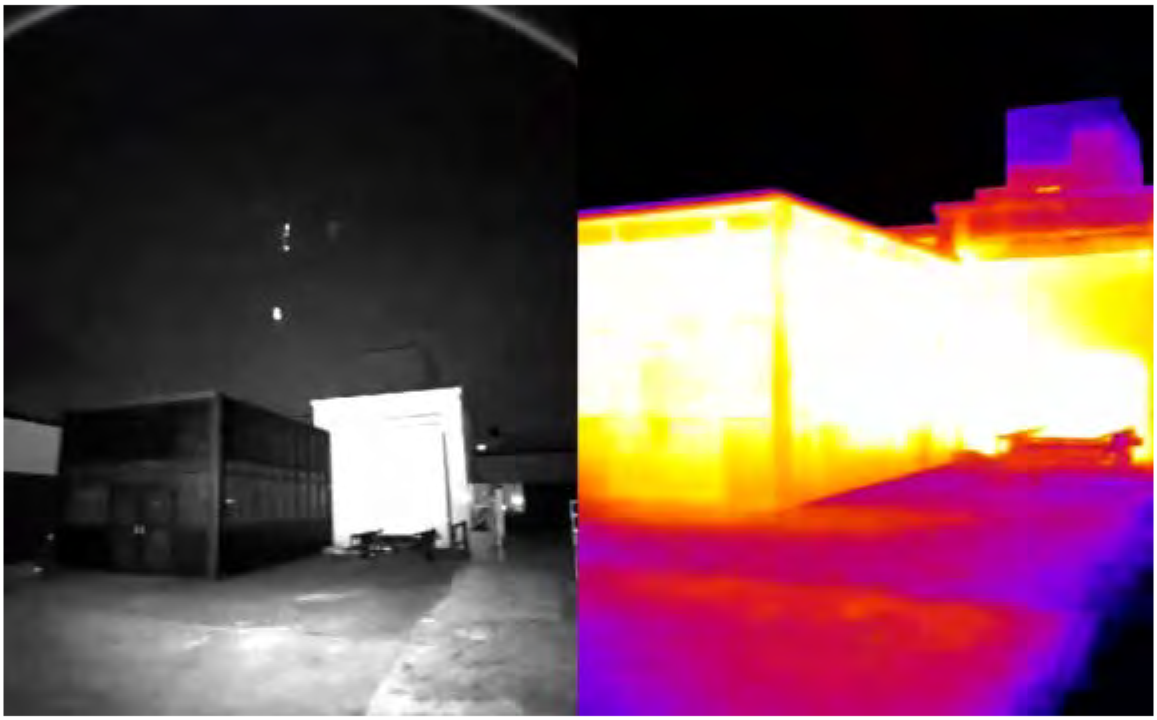
Figure D-76. Aerial view of Bldg 1529, Scott AFB.

Figure D-77. Thermal image of Bldg 1529, Scott AFB.

D.16.2 Notable leaks at Bldg 1529, Scott AFB

At timestamp 145:53 in the Drive-by Application there is a very emissive loading bay door and entryway (Figure D-78). This is one of the most emissive buildings on the entire base. This building should be investigated for insulation problems and insulation should be added to the entire loading bay.

Figure D-78. NIR image (left) and thermal image (right) of Bldg 1529, Scott AFB.



D.16.3 Envelope ECMs for Bldg 1529, Scott AFB

Figure D-79 shows the relative ROI for envelope ECMs for Bldg 1529, Scott AFB.

Figure D-79. ECM profile for Bldg 1529, Scott AFB.

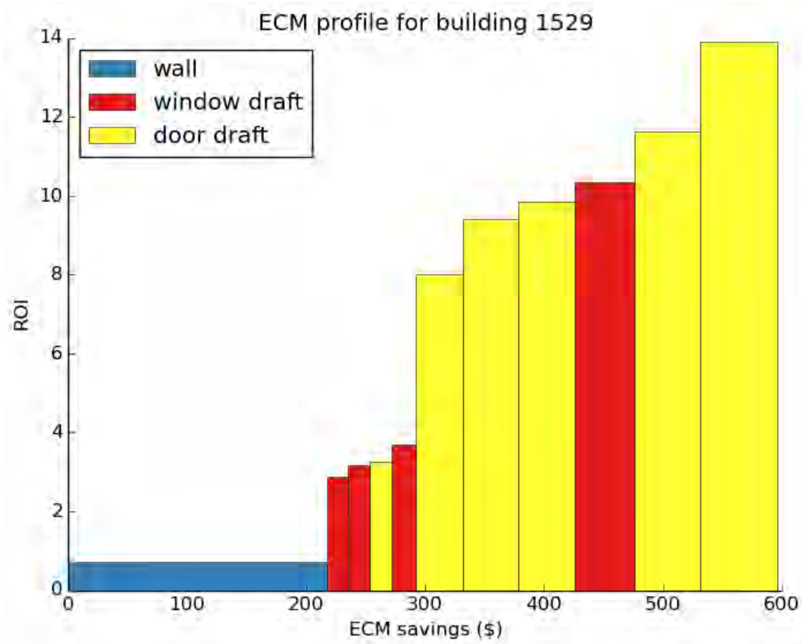


Table 16 lists the recommended envelope ECMs for Bldg 1529, Scott AFB.

Table 16. Envelope ECMs for Bldg 1529, Scott AFB.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Seal Door Frame Leaks	185	444	273	396	1.5
Improve Wall Insulation	147	355	218	1891	8.7
Seal Window Frame Leaks	72	172	106	264	2.5

Annual potential remediation savings for this building are $596 and total payback is 4.3 years for envelope-related ECMs.

D.17 Bldg 1575

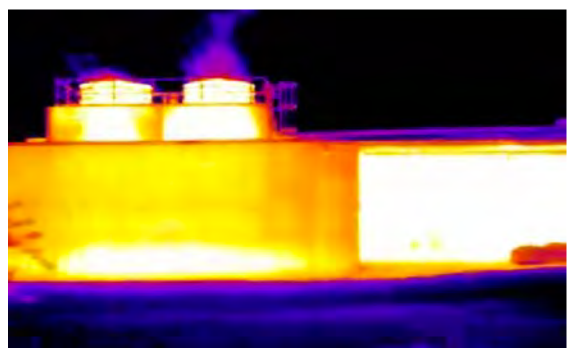
D.17.1 Description of Bldg 1575, Scott AFB

Name: Comm Facility (NOSC)
Use Type: Office
Square Footage: 50,957
Avg. Daily Electric Use: 26,100 kWh
Avg. Daily Gas Use: 36.4 therms
Electricity Score: 100th Percentile
Gas Score: 30th Percentile
Annual Cooling Load: 274,624 kWhrs
Annual Heating Load: 15,346 therms

Bldg 1575 (Figures D-80 and D-81) has a gas usage of 26,072 Btu/sq ft/yr and electricity usage of 186.9 kWh/sq ft/yr.

Figure D-80. Aerial view of Bldg 1575, Scott AFB.

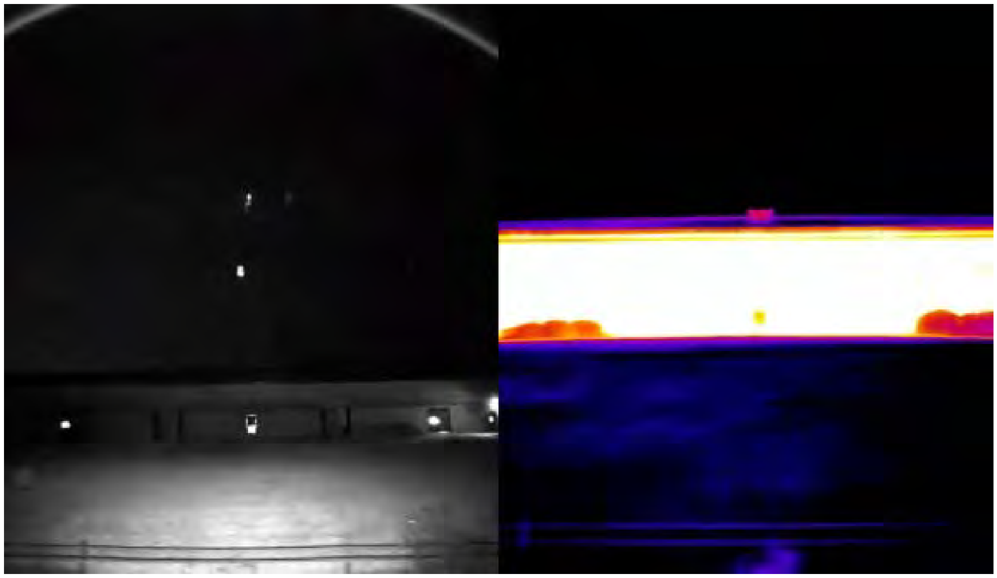
Figure D-81. Thermal image of Bldg 1575, Scott AFB.



D.17.2 Notable leaks at Bldg 1575, Scott AFB

The walls of Bldg 1575, shown at timestamp 151:19, are so highly emissive in general that specific features are not visible (Figure D-82). This was the worst insulation problem of any building on the base. It is recommended to investigate the current insulation levels in the walls and the need to add insulation along the entire wall.

Figure D-82. NIR image (left) and thermal image (right) of Bldg 1575, Scott AFB.



D.17.3 Envelope ECMs for Bldg 1575, Scott AFB

Figure D-83 shows the relative ROI for envelope ECMs for Bldg 1575, Scott AFB.

Figure D-83. ECM profile for Bldg 1575, Scott AFB.

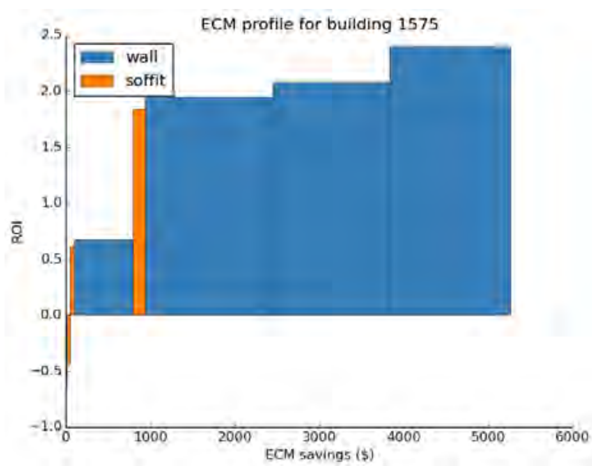


Table 17 lists the recommended envelope ECMs for Bldg 1575, Scott AFB.

Table 17. Envelope ECMs for Bldg 1575, Scott AFB.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Improve Wall Insulation	3403	8196	5026	26992	5.4
Improve Soffit Insulation	126	303	186	1138	6.1

Annual potential remediation savings for this building are $5,212 and total payback is 5.4 years for envelope-related ECMs.

D.18 Bldg 1600

D.18.1 Description of Bldg 1600, Scott AFB

Name: HQ Major Cmd
Use Type: Office
Square Footage: 313,330
Avg. Daily Electric Use: 37,618 kWh
Avg. Daily Gas Use: 455.1 therms
Electricity Score: 95th Percentile
Gas Score: 80th Percentile
Annual Cooling Load: 549,164 kWhrs
Annual Heating Load: 31,865 therms

Bldg 1600 (Figures D-84 and D-85) has a gas usage of 52,999 Btu/sq ft/yr and electricity usage of 43.8 kWh/sq ft/yr.

Figure D-84. Aerial view of Bldg 1600, Scott AFB.

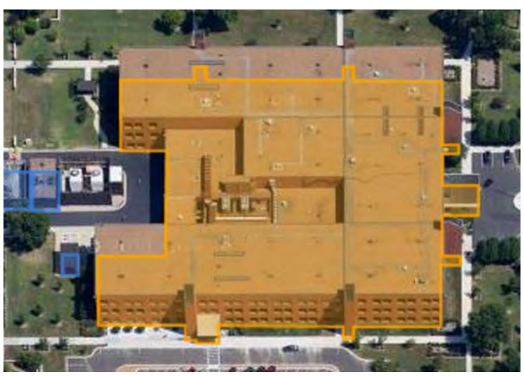
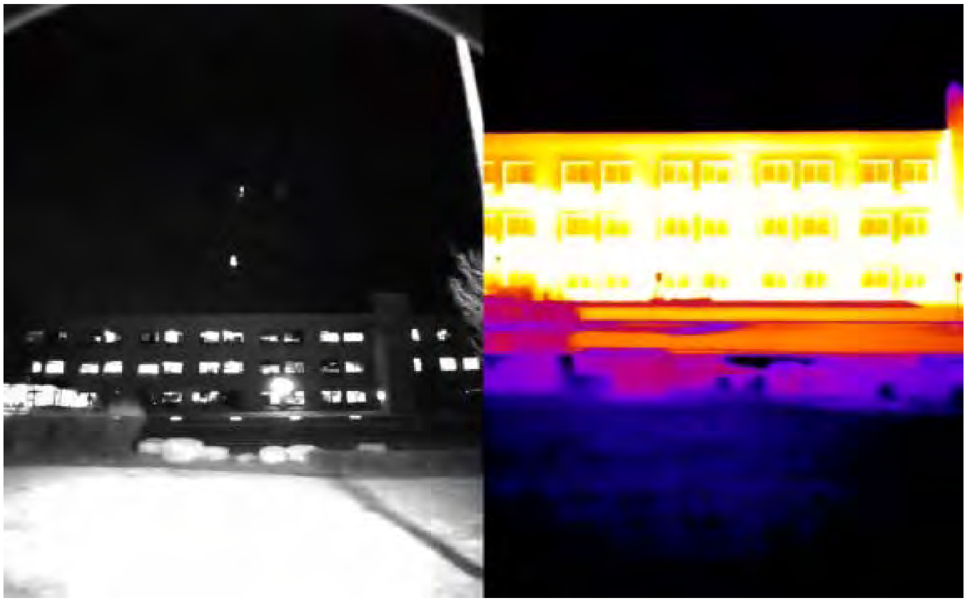


Figure D-85. Thermal image of Bldg 1600, Scott AFB.

D.18.2 Notable leaks at Bldg 1600, Scott AFB

Bldg 1600 has particularly emissive striations between the windows in the lower part of the building, visible at timestamp 167:11 (Figure D-86). The thermal scan indicates insulation issues between windows for the first two floors of the building. This should be investigated to determine whether the cause is sagging insulation, low insulation, or areas with no insulation.

Figure D-86. NIR image (left) and thermal image (right) of Bldg 1600, Scott AFB.



D.18.3 Envelope ECMs for Bldg 1600, Scott AFB

Figure D-87 shows the relative ROI for envelope ECMs for Bldg 1600, Scott AFB.

Figure D-87. ECM profile for Bldg 1600, Scott AFB.

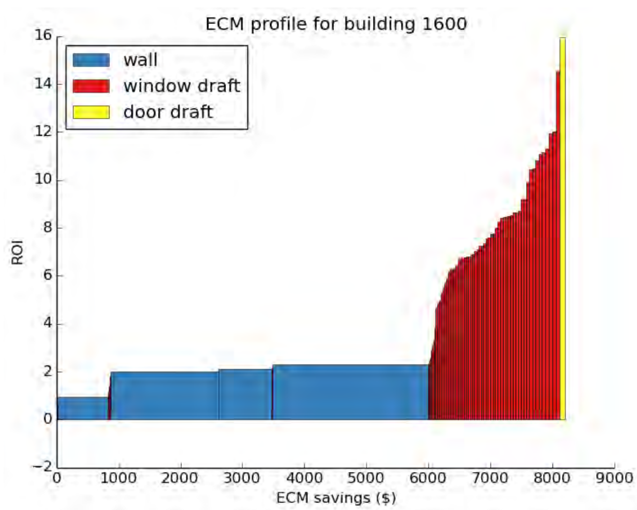


Figure D-35 lists the recommended envelope ECMs for Bldg 1600, Scott AFB.

Table 18. Envelope ECMs for Bldg 1600, Scott AFB.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Improve Wall Insulation	4008	9648	5917	30557	5.2
Seal Window Frame Leaks	1489	3587	2200	4341	2.0
Seal Door Frame Leaks	51	122	75	66	0.9

Annual potential remediation savings for this building are $8,911 and total payback is 4.3 years for envelope-related ECMs.

D.19 Bldg 1650

D.19.1 Description of Bldg 1650, Scott AFB

Name: Airman Family Readiness Center
Use Type: School
Square Footage: 72,205
Avg. Daily Electric Use: 1,619 kWh
Avg. Daily Gas Use: 47.9 therms
Electricity Score: 40th Percentile
Gas Score: 20th Percentile
Annual Cooling Load: 77,446 kWhrs
Annual Heating Load: 17,225 therms

Bldg 1650 (Figures D-88 and D-88) has a gas usage of 24,191 Btu/sq ft/yr and electricity usage of 8.2 kWh/sq ft/yr.

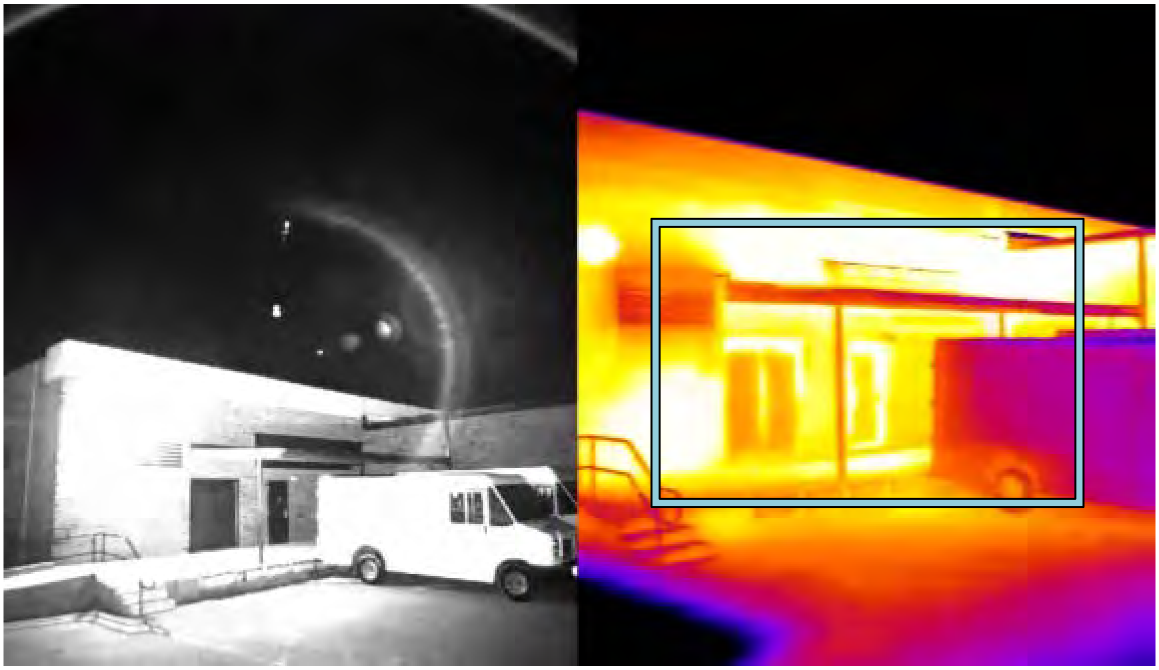
Figure D-88. Aerial view of Bldg 1650, Scott AFB.

Figure D-89. Thermal image of Bldg 1650, Scott AFB.

D.19.2 Notable leaks at Bldg 1650, Scott AFB

Notable emissive wall surfaces are visible at timestamp 161:21, to the left of the double doors and near the top of the building wall. This building wall has an insulation issue along with significant leaks around both the double doors and the single door to the right. The door energy loss can be remediated through weather-stripping.

Figure D-90. NIR image (left) and thermal image (right) of Bldg 1650, Scott AFB.



The door frame visible at timestamp 162:27 indicates convective leaks along the outer frame. The wall is also losing energy. This would also be a good candidate for adding insulation to the wall and weather-stripping to the door.

Figure D-91. NIR image (left) and thermal image (right) of Bldg 1650, Scott AFB. There appears to be significant energy loss around the door frame.

D.19.3 Envelope ECMs for Bldg 1650, Scott AFB

Figure D-92 shows the relative ROI for envelope ECMs for Bldg 1650, Scott AFB.

Figure D-92. ECM profile for Bldg 1650, Scott AFB.

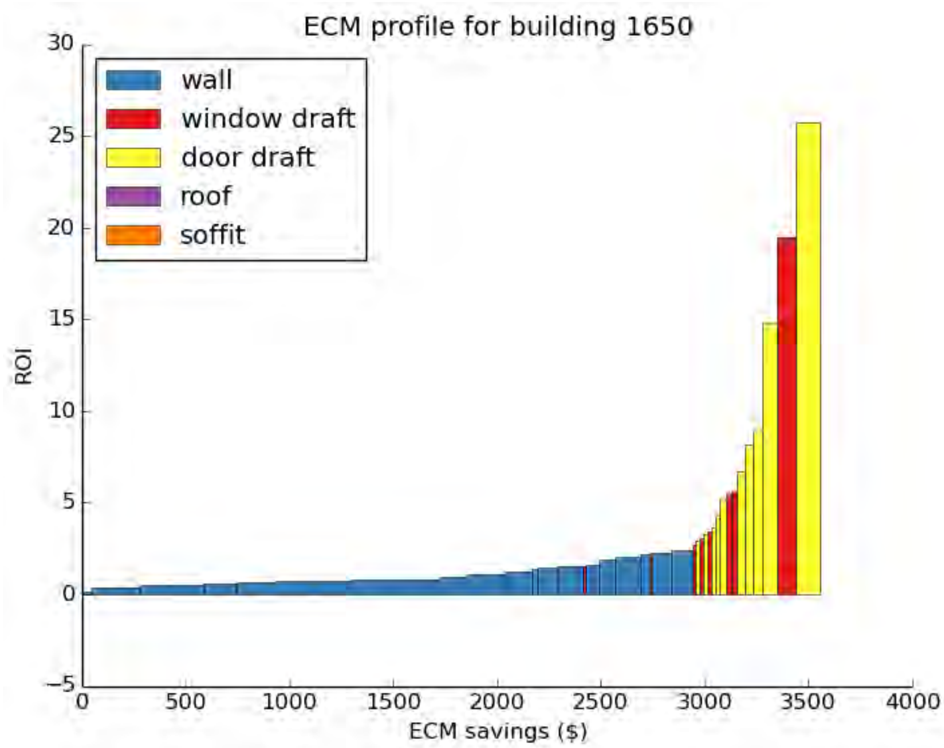


Table 19 lists the recommended envelope ECMs for Bldg 1650, Scott AFB.

Table 19. Envelope ECMs for Bldg 1650, Scott AFB.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Improve Wall Insulation	1965	4731	2901	23218	8.0
Seal Door Frame Leaks	280	673	413	661	1.6
Seal Window Frame Leaks	148	358	219	527	2.4

Annual potential remediation savings for this building are $3,534 and total payback is 6.9 years for envelope-related ECMs.

D.20 Bldg 1900

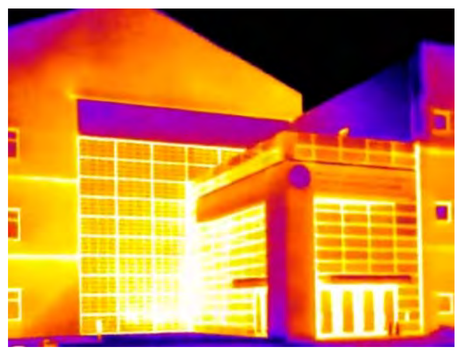
D.20.1 Description of Bldg 1900, Scott AFB

Name: USTRANSCOMM
Use Type: Office
Square Footage: 335,771
Avg. Daily Electric Use: 30,958 kWh
Avg. Daily Gas Use: 150.4 therms
Electricity Score: 75th Percentile
Gas Score: 15th Percentile
Annual Cooling Load: 471,562 kWhrs
Annual Heating Load: 17,397 therms

Bldg 1900 (Figures D-93 and D-94) has a gas usage of 16,347 Btu/sq ft/yr and electricity usage of 33.7 kWh/sq ft/yr.

Figure D-93. Aerial view of Bldg 1900, Scott AFB.

Figure D-94. Thermal image of Bldg 1900, Scott AFB.



D.20.2 Notable leaks at Bldg 1900, Scott AFB

There are some large thermal bridges stretching both across the wall and from ground to roof around timestamp 34:58 (Figure D-95).

Figure D-95. NIR image (left) and thermal image (right) of Bldg 1900, Scott AFB.

Thermal bridges are also visible around the other side of the building at timestamp 35:22 (Figure D-96). The window frames are also fairly emissive. Window frame leaks can be addressed by caulking and weather-stripping. There is also a thermal bridge between the first and second floors and the second and third floor.

Figure D-96. NIR image (left) and thermal image (right) of Bldg 1900, Scott AFB. Thermal bridges are apparent between the rows of windows.

D.20.3 Envelope ECMs for Bldg 1900, Scott AFB

Figure D-97 shows the relative ROI for envelope ECMs for Bldg 1900, Scott AFB.

Figure D-97. ECM profile for Bldg 1900, Scott AFB.

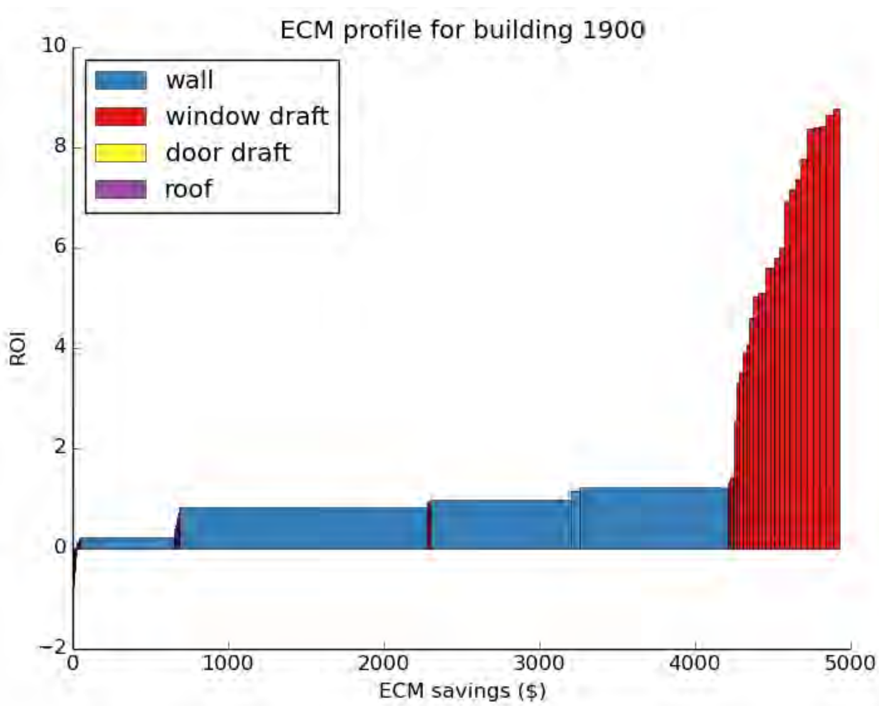


Table 20 lists the recommended envelope ECMs for Bldg 1900, Scott AFB.

Table 20. Envelope ECMs for Bldg 1900, Scott AFB.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Improve Wall Insulation	2775	6690	4102	34463	8.4
Seal Window Frame Leaks	542	1306	801	2570	3.2

Annual potential remediation savings for this building are $4,903 and total payback is 7.6 years for envelope-related ECMs.

D.21 Bldg 1961

D.21.1 Description of Bldg 1961, Scott AFB

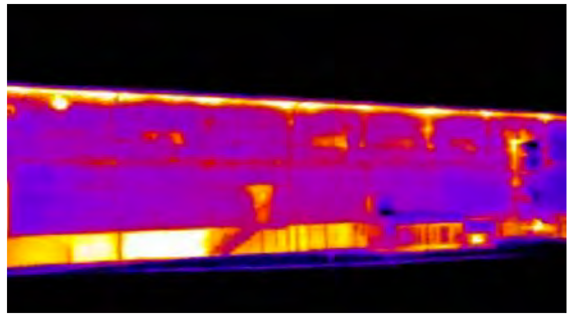
Name: USTRANSCOMM Annex
Use Type: Office
Square Footage: 80,284
Avg. Daily Electric Use: 5,694 kWh
Avg. Daily Gas Use: 63.7 therms
Electricity Score: 60th Percentile
Gas Score: 50th Percentile
Annual Cooling Load: 614,284 kWhrs
Annual Heating Load: 18,071 therms

Bldg 1961 (Figures D-98 and D-99) serves as an interesting example of how energy use per square foot is not always a good predictor of leakiness or remediation potential. The building is perhaps the most obviously incompletely insulated building on the base, with numerous large hot spots scattered all over the exterior. However, its gas score only puts it in the 50th percentile, meaning that about half the buildings of a similar square footage have higher gas usage per square foot. The electricity use is a similarly middling 60th percentile.

Bldg 1961 has a gas usage of 28,960 Btu/sq ft/yr and electricity usage of 25.9 kWh/sq ft/yr.

Figure D-98. Aerial view of Bldg 1961, Scott AFB.

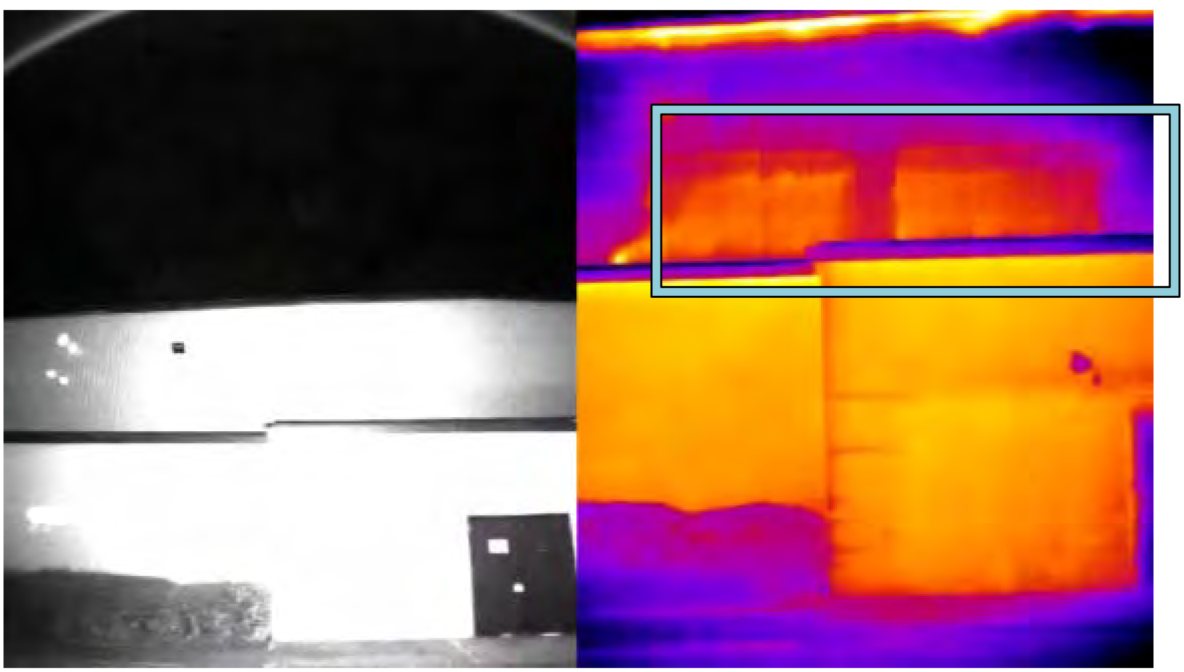
Figure D-99. Thermal image of Bldg 1961, Scott AFB.



D.21.2 Notable leaks at Bldg 1961, Scott AFB

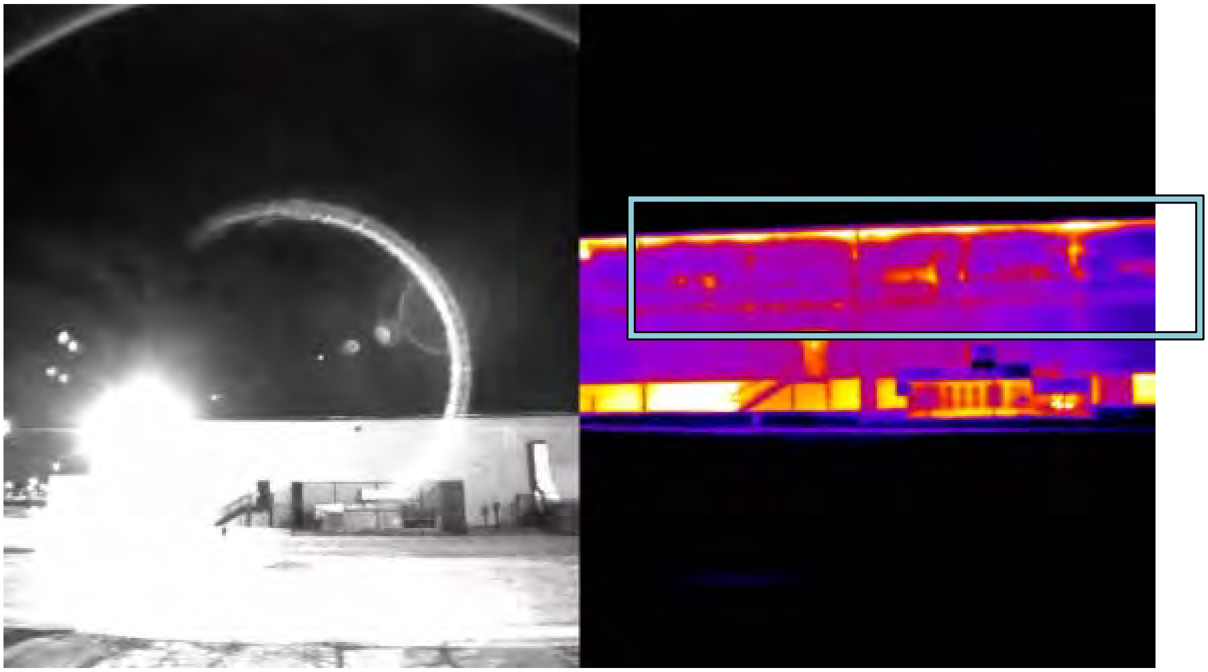
There is a sizable patch of poorly insulated wall on the second story of the building around timestamp 42:55. The soffit also appears to be highly emissive (Figure D-100).

Figure D-100. NIR image (left) and thermal image (right) of Bldg 1961, Scott AFB.



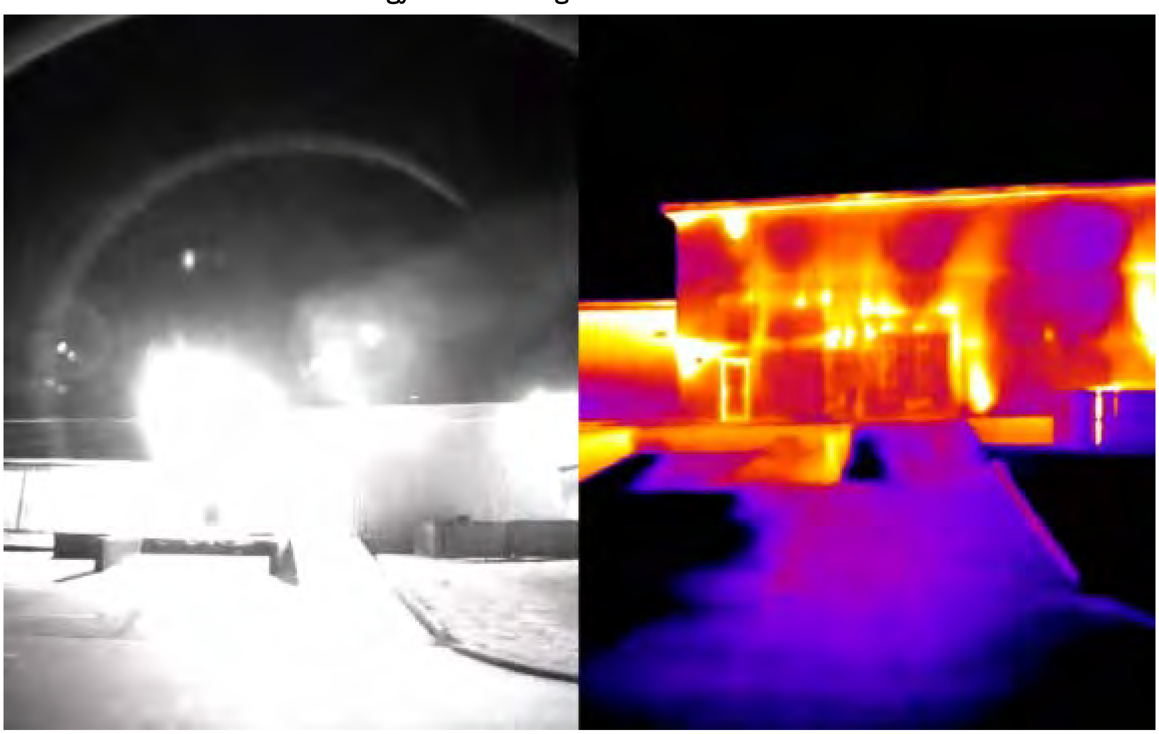
There are numerous wall insulation gaps around the back of the building around timestamp 43:11, as well as a leaky soffit (Figure D-101).

Figure D-101. NIR image (left) and thermal image (right) of Bldg 1961, Scott AFB. Note numerous wall insulation gaps around the back of the building as well as a leaky soffit.



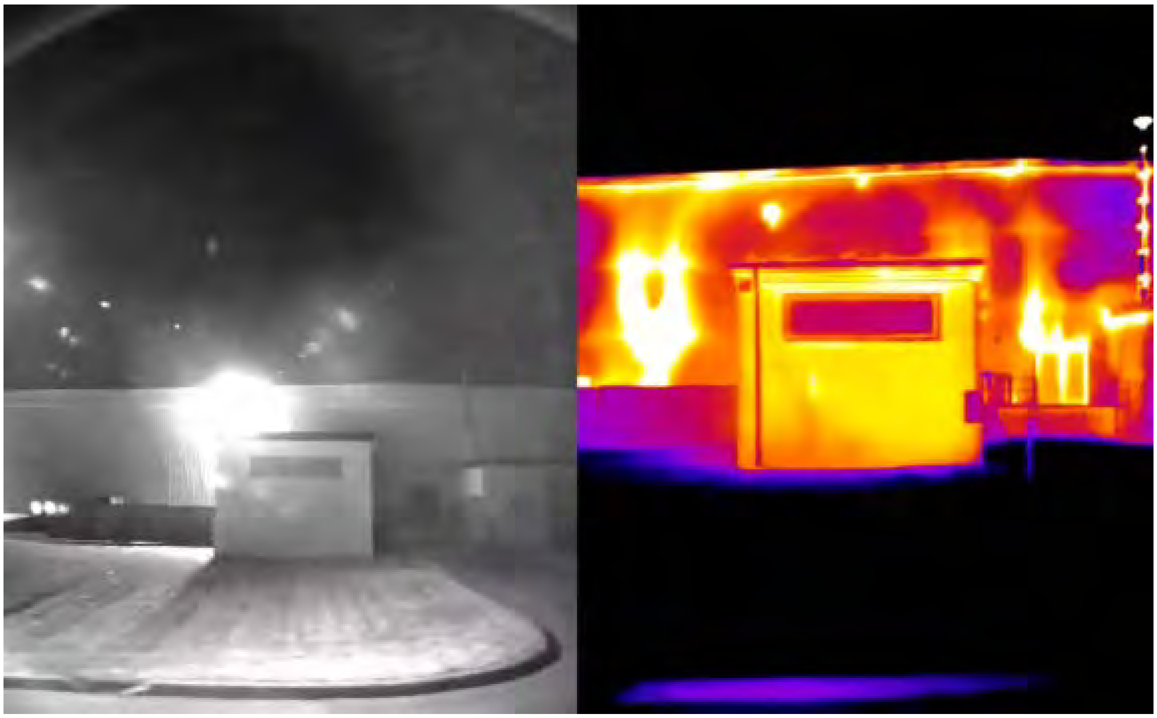
The back of the building around timestamp 43:31 is particularly emissive, with large amounts of heat leaking out (Figure D-102). The wall has insulation problems.

Figure D-102. NIR image (left) and thermal image (right) of Bldg 1961, Scott AFB. Significant energy losses through this wall is indicated.



Similar large leaks are seen on the wall at timestamp 43:32 (Figure D-103). The "patchy appearance" indicates inconsistent insulation throughout the wall. The double doors to the right of the image may also have notable convective leaks around the frame.

Figure D-103. NIR image (left) and thermal image (right) of Bldg 1961, Scott AFB. The "patchy appearance" indicates inconsistent insulation throughout the wall.



D.21.3 Envelope ECMs for Bldg 1961, Scott AFB

Figure D-104 shows the relative ROI for envelope ECMs for Bldg 1961, Scott AFB.

Figure D-104. ECM profile for Bldg 1961, Scott AFB.

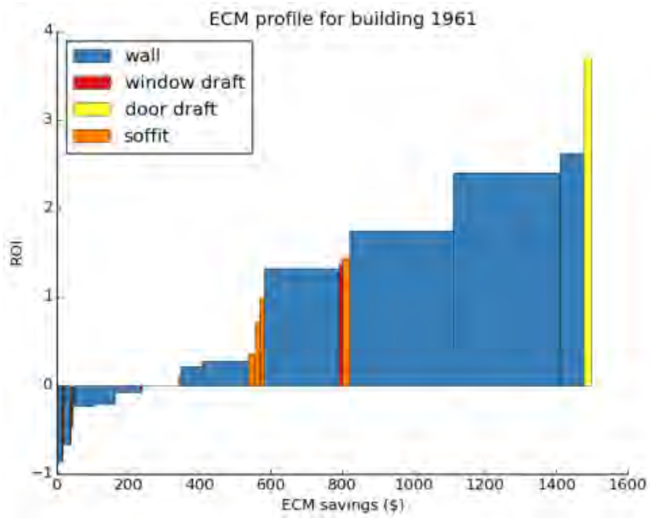


Table 21 lists the recommended envelope ECMs for Bldg 1961, Scott AFB.

Table 21. Envelope ECMs for Bldg 1961, Scott AFB.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Improve Wall Insulation	714	1721	1055	6818	6.5
Improve Soffit Insulation	47	114	70	612	8.8
Seal Door Frame Leaks	14	34	21	66	3.2
Seal Window Frame Leaks	7	17	10	66	6.3

Annual potential remediation savings for this building are $1,156 and total payback is 6.5 years for envelope-related ECMs.

D.22 Bldg 1980

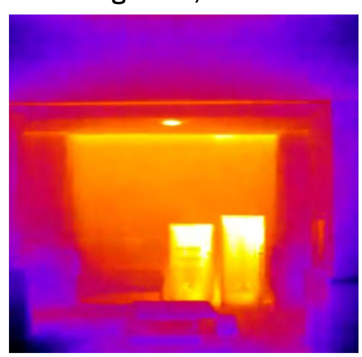
D.22.1 Description of Bldg 1980, Scott AFB

Name: Store Commissary
Use Type: Grocery
Square Footage: 113,652
Avg. Daily Electric Use: 12,090 kWh
Avg. Daily Gas Use: 116.0 therms
Electricity Score: 85th Percentile
Gas Score: 70th Percentile
Annual Cooling Load: 279,138 kWhrs
Annual Heating Load: 21,977 therms

Bldg 1980 (Figure D-105 and D-106) has a gas usage of 37,240 Btu/sq ft/yr and electricity usage of 38.8 kWh/sq ft/yr.

Figure D-105. Aerial view of Bldg 1980, Scott AFB.

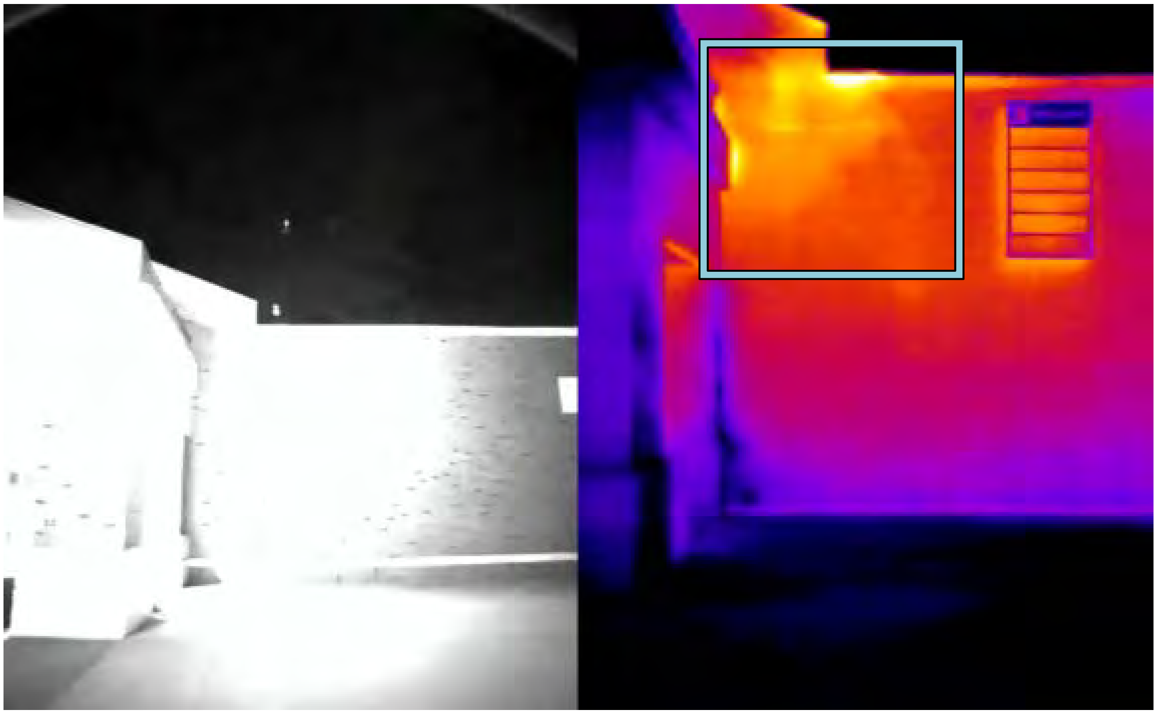
Figure D-106. Thermal image of Bldg 1980, Scott AFB.



D.22.2 Notable leaks at Bldg 1980, Scott AFB

Bldg 1980 has a hot spot on the wall around timestamp 173:46, indicating poor or incomplete wall insulation at that spot (Figure D-107).

Figure D-107. NIR image (left) and thermal image (right) of Bldg 1980, Scott AFB.



D.22.3 Envelope ECMs for Bldg 1980, Scott AFB

Figure D-108 shows the relative ROI for envelope ECMs for Bldg 1980, Scott AFB.

Figure D-108. ECM profile for Bldg 1980, Scott AFB.

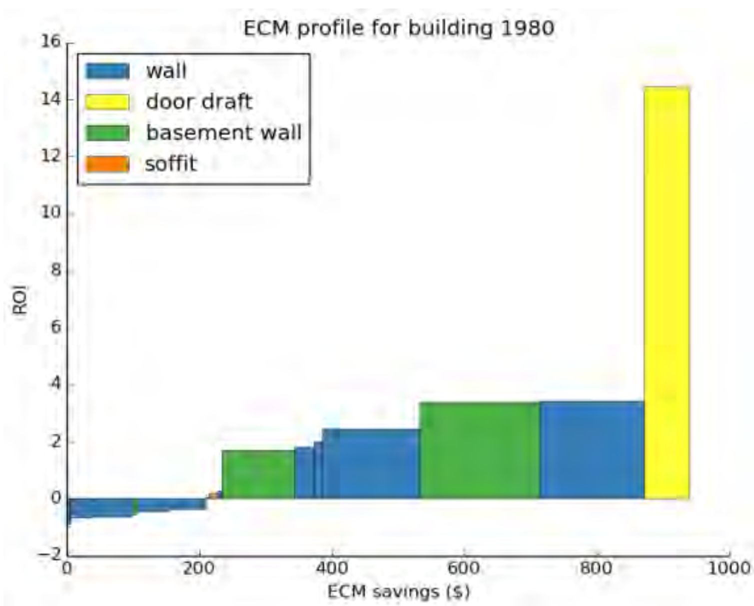


Table 22 lists the recommended envelope ECMs for Bldg 1980, Scott AFB.

Table 22. Envelope ECMs for Bldg 1980, Scott AFB.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Improve Wall Insulation	243	584	358	1534	4.3
Basement Wall Insulation	196	472	289	1223	4.2
Seal Door Frame Leaks	46	111	68	66	1.0
Improve Soffit Insulation	9	21	13	165	12.6

Annual potential remediation savings for this building are $729 and total payback is 4.1 years for envelope-related ECMs.

D.23 Bldg 3189

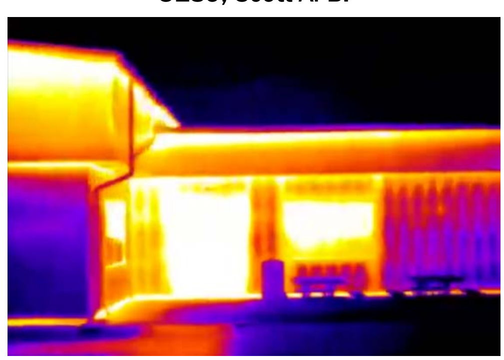
D.23.1 Description of Bldg 3189, Scott AFB

Name: Admin Ofc Non-Af (DECCO)
Use Type: Office
Square Footage: 71,962
Avg. Daily Electric Use: 5,673 kWh
Avg. Daily Gas Use: 28.7 therms
Electricity Score: 70th Percentile
Gas Score: 10th Percentile
Annual Cooling Load: 55,139 kWhrs
Annual Heating Load: 9,164 therms

Bldg 3189 (Figures D-109 and D-110) has a gas usage of 14,572 Btu/sq ft/yr and electricity usage of 28.8 kWh/sq ft/yr.

Figure D-109. Aerial view of Bldg 3189, Scott AFB.

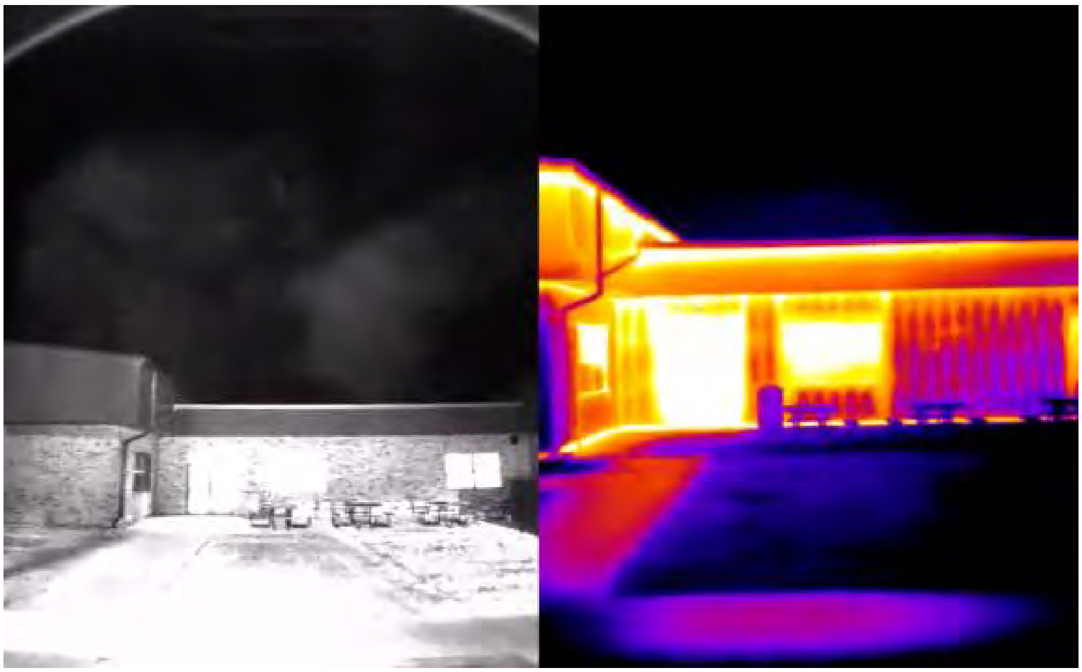
Figure D-110. Thermal image of Bldg 3189, Scott AFB.



D.23.2 Notable leaks at Bldg 3189, Scott AFB

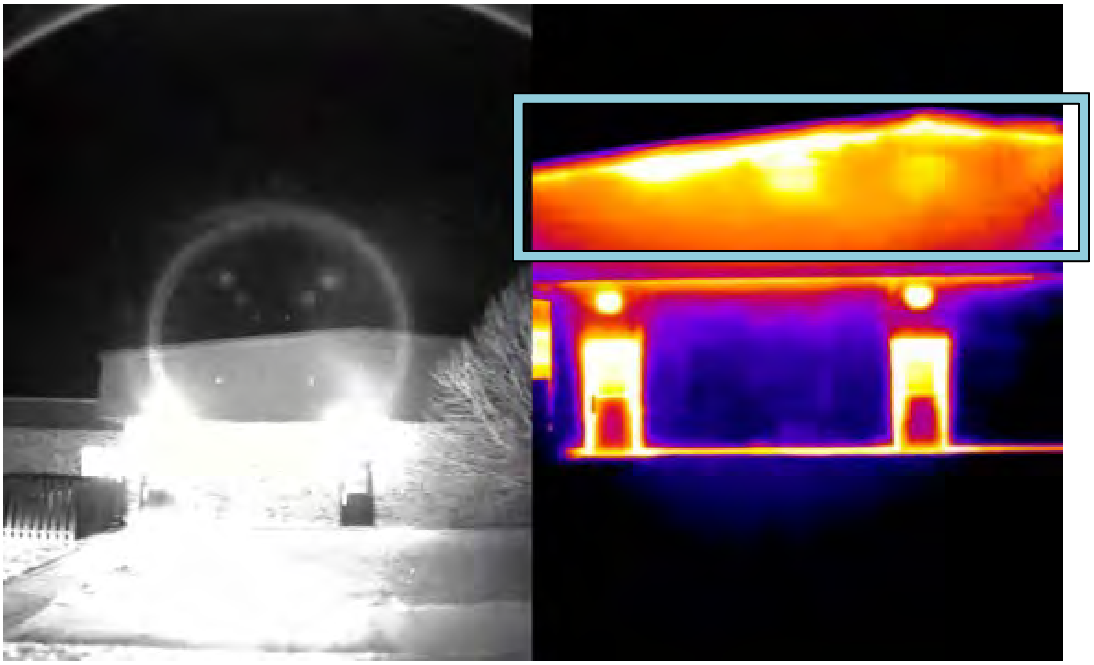
Bldg 3189 has numerous thermal bridges or insulation holes behind the brick wall around timestamp 113:30 (Figure D-111). As seen in other buildings, the large garage door is very leaky. There is also significant energy leakage through the soffit.

Figure D-111. NIR image (left) and thermal image (right) of Bldg 3189, Scott AFB.



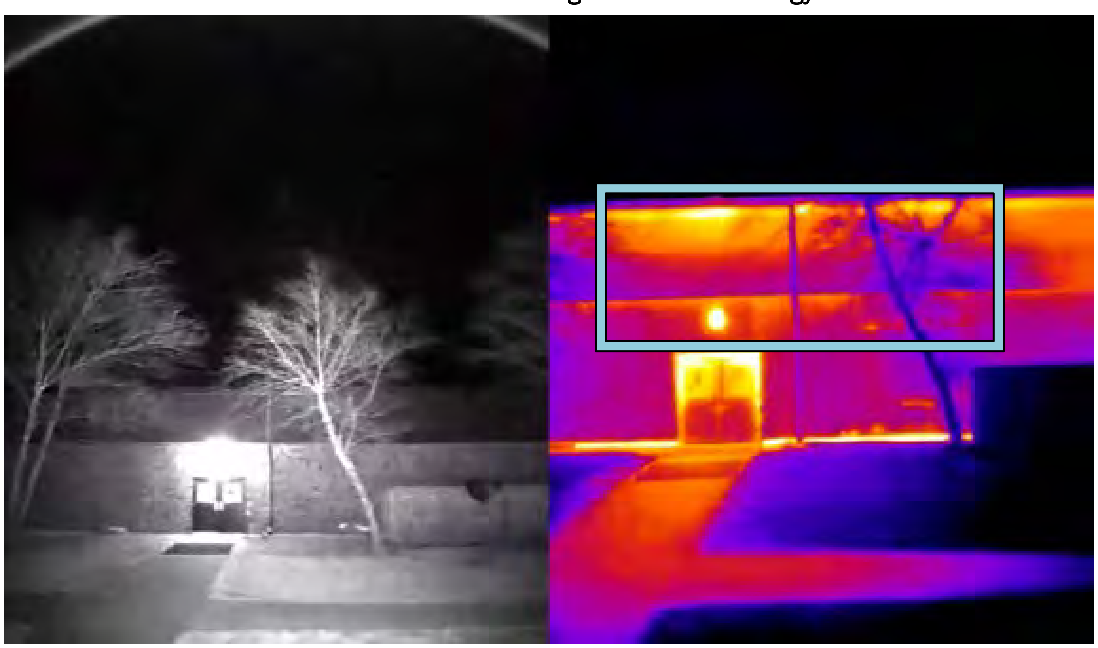
The soffit and door frames around timestamp 113:32 are notably leaky (Figure D-112). The area outlined by the polygon is showing poor insulation. Both doors are also very leaky.

Figure D-112. NIR image (left) and thermal image (right) of Bldg 3189, Scott AFB. The soffit and door frames appear to be notably leaky.



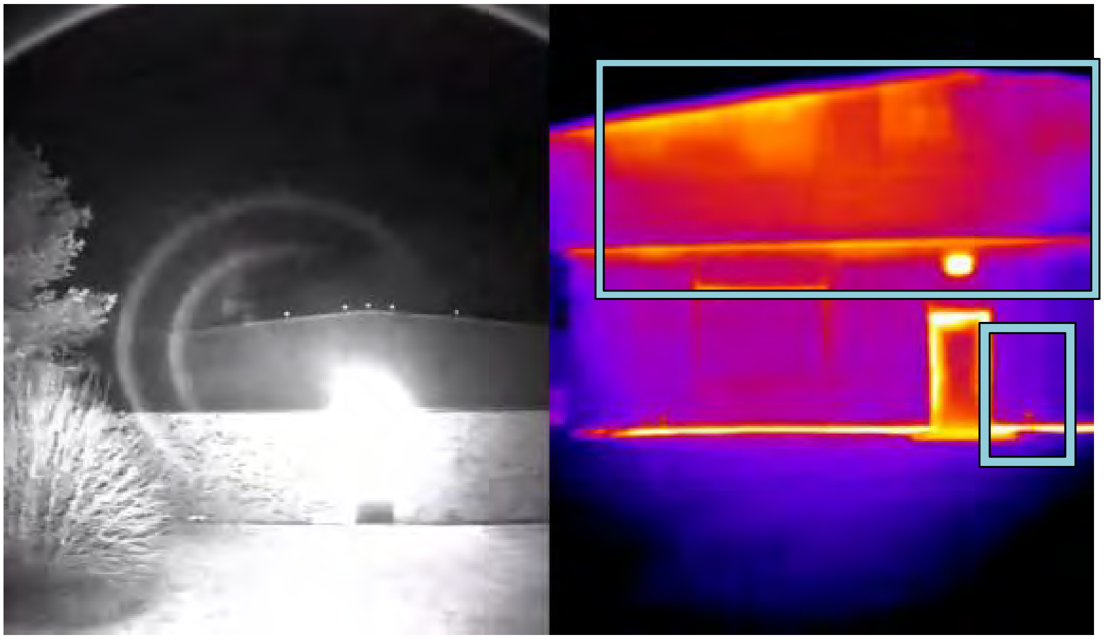
The soffit/roof around 113:49 remains fairly emissive (Figure D-113). The top of the double doors are also losing energy.

Figure D-113. NIR image (left) and thermal image (right) of Bldg 3189, Scott AFB. The top of the double doors are losing considerable energy.



The soffit and roof line at timestamp 113:57 is fairly emissive, and the door frame may have a sizable convective leak (Figure D-114). It is recommended that weather-stripping be added to the door to prevent energy loss from the door frame.

Figure D-114. NIR image (left) and thermal image (right) of Bldg 3189, Scott AFB. The soffit and roof line are fairly emissive.



D.23.3 Envelope ECMs for Bldg 3189, Scott AFB

Figure D-115 shows the relative ROI for envelope ECMs for Bldg 3189, Scott AFB.

Figure D-115. ECM profile for Bldg 3189, Scott AFB.

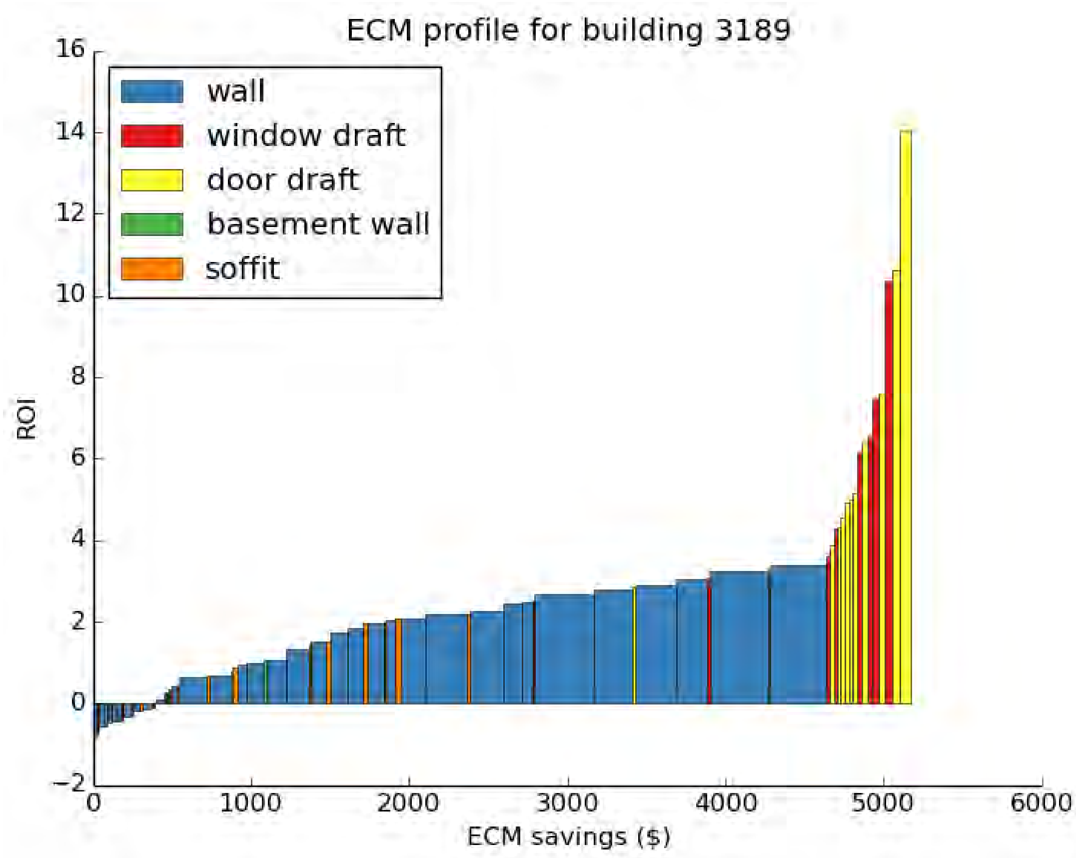


Table 23 lists the recommended envelope ECMs for Bldg 3189, Scott AFB.

Table 23. Envelope ECMs for Bldg 3189, Scott AFB.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Improve Wall Insulation	2648	6376	3910	20021	5.1
Seal Door Frame Leaks	248	598	367	791	2.2
Seal Window Frame Leaks	166	399	245	723	3.0
Improve Soffit Insulation	140	336	206	1429	6.9
Basement Wall Insulation	36	86	52	430	8.2

Annual potential remediation savings for this building are $4,780 and total payback is 4.9 years for envelope-related ECMs.

D.24 Bldg 3689

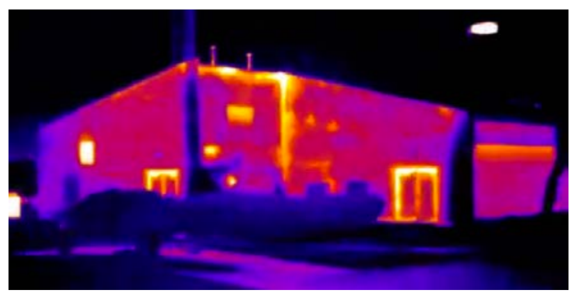
D.24.1 Description of Bldg 3689, Scott AFB

Name: Acw Ops Bldg
Use Type: Misc
Square Footage: 4,720
Avg. Daily Electric Use: 391 kWh
Avg. Daily Gas Use: 4.7 therms
Electricity Score: 80th Percentile
Gas Score: 15th Percentile
Annual Cooling Load: 5,811 kWhrs
Annual Heating Load: 1,681 therms

Bldg 3689 (Figures D-116 and D-117) has a gas usage of 36,307 Btu/sq ft/yr and electricity usage of 30.2 kWh/sq ft/yr.

Figure D-116. Aerial view of Bldg 3689, Scott AFB.

Figure D-117. Thermal image of Bldg 3689, Scott AFB.



D.24.2 Notable leaks at Bldg 3689, Scott AFB

The wall of Bldg 3689 at timestamp 122:48 has a number of emissive patches, which indicate holes (Figure D-118)). There is also a large hot stripe at the juncture in the middle of the image that may be worth investigating further. The double doors on the right of the image are also leaking energy. Weather-stripping is recommended to fix energy leaking around the door frame.

Figure D-118. NIR image (left) and thermal image (right) of Bldg 3689, Scott AFB.

D.24.3 Envelope ECMs for Bldg 3689, Scott AFB

Figure D-119 shows the relative ROI for envelope ECMs for Bldg 3689, Scott AFB.

Figure D-119. ECM profile for Bldg 3689, Scott AFB.

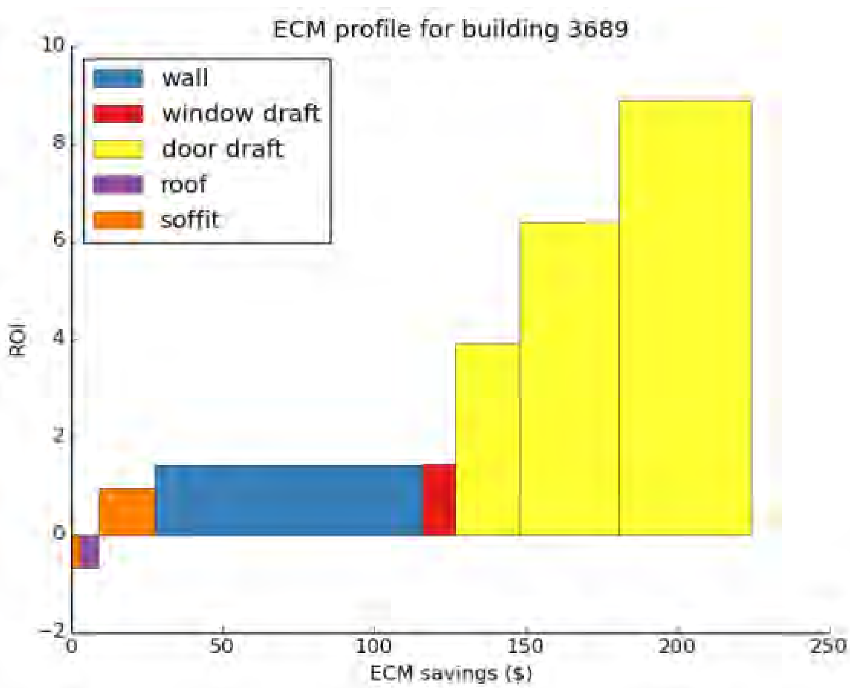


Table 24 lists the recommended envelope ECMs for Bldg 3689, Scott AFB.

Table 24. Envelope ECMs for Bldg 3689, Scott AFB.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Seal Door Frame Leaks	66	159	98	198	2.0
Improve Wall Insulation	60	144	88	547	6.2
Improve Soffit Insulation	13	30	19	144	7.7
Seal Window Frame Leaks	7	17	11	66	6.2

Annual potential remediation savings for this building are $215 and total payback is 4.4 years for envelope-related ECMs.

D.25 Bldg 4001

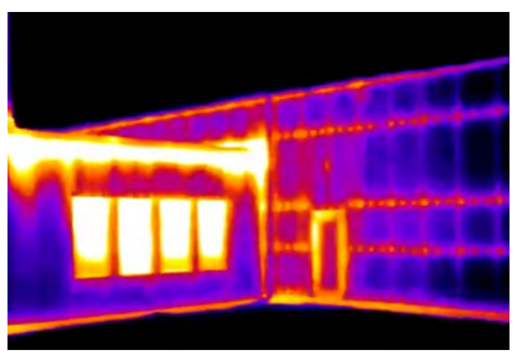
D.25.1 Description of Bldg 4001, Scott AFB

Name: Whse Sup & Equip Bse
Use Type: Warehouse
Square Footage: 81,094
Avg. Daily Electric Use: Not Provided
Avg. Daily Gas Use: 67.5 therms
Electricity Score: N/A
Gas Score: 40th Percentile
Annual Cooling Load: N/A
Annual Heating Load: 23,896 therms

Bldg 4001 (Figures D-120 and D-121) has a gas usage of 30,389 Btu/sq ft/yr.

Figure D-120. Aerial view of Bldg 4001, Scott AFB.

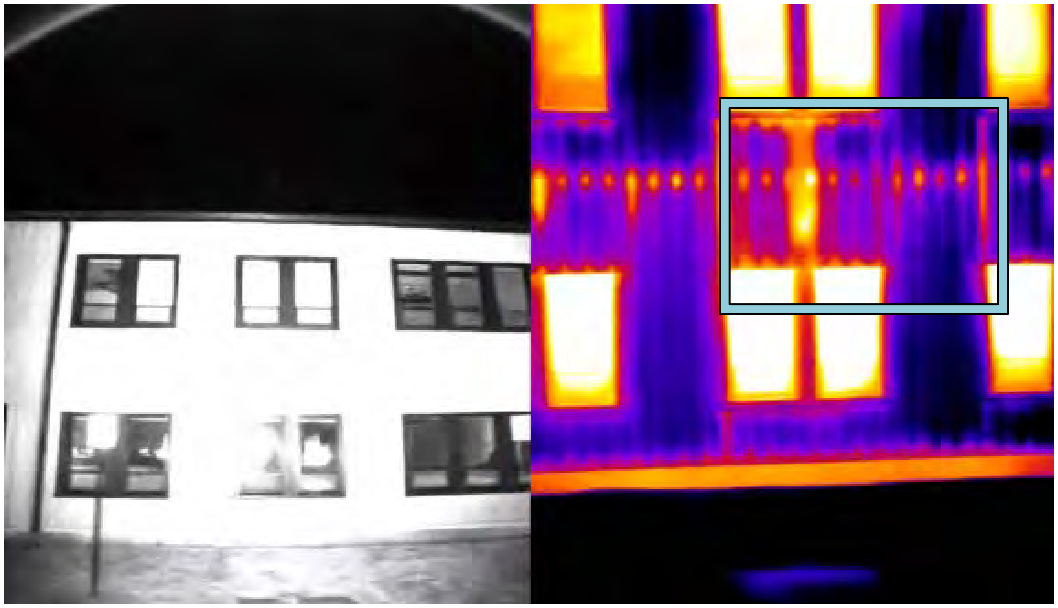
Figure D-121. Thermal image of Bldg 4001, Scott AFB.



D.25.2 Notable leaks at Bldg 4001, Scott AFB

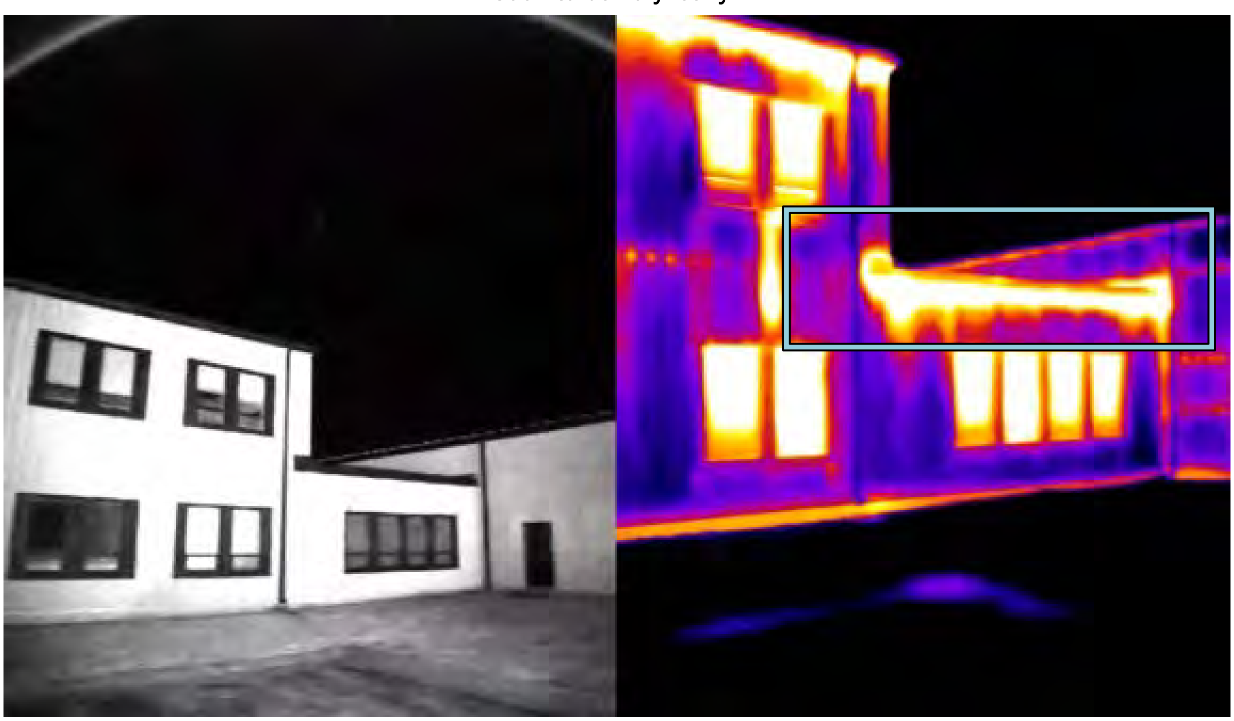
There are thermal bridges due to rivets around timestamp 97:50, as well as some larger hot patches that may be insulation holes (Figure D-122).

Figure D-122. NIR image (left) and thermal image (right) of Bldg 4001, Scott AFB.



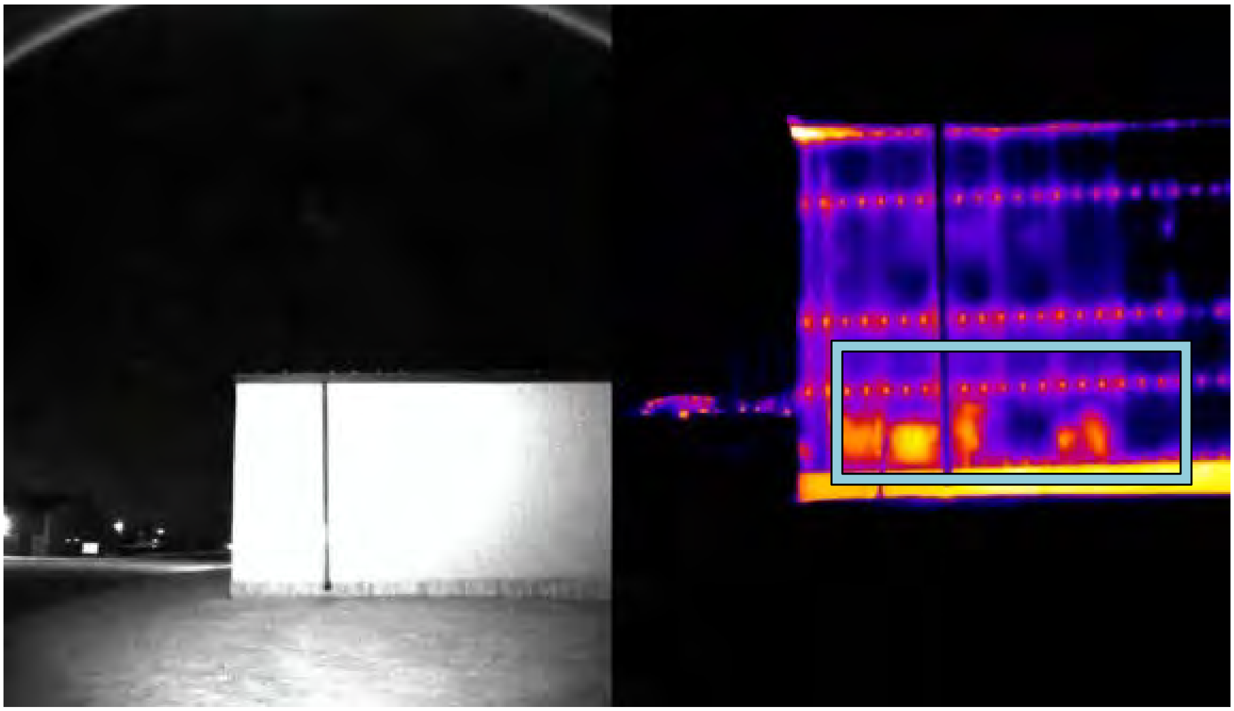
Timestamp 97:51 shows some particularly leaky soffits, as well as a large insulation hole between upper and lower windows on the left side of the image (Figure D-123).

Figure D-123. NIR image (left) and thermal image (right) of Bldg 4001, Scott AFB. Soffits are seen to be very leaky.



There are some additional insulation holes around the back at timestamp 98:12. The hotspots observed through the entire building indicate thermal bridges (Figure D-124).

Figure D-124. NIR image (left) and thermal image (right) of Bldg 4001, Scott AFB. The hot spots indicate thermal bridges.



D.25.3 Envelope ECMs for Bldg 4001, Scott AFB

Figure D-125 shows the relative ROI for envelope ECMs for Bldg 4001, Scott AFB.

Figure D-125. ECM profile for Bldg 4001, Scott AFB.

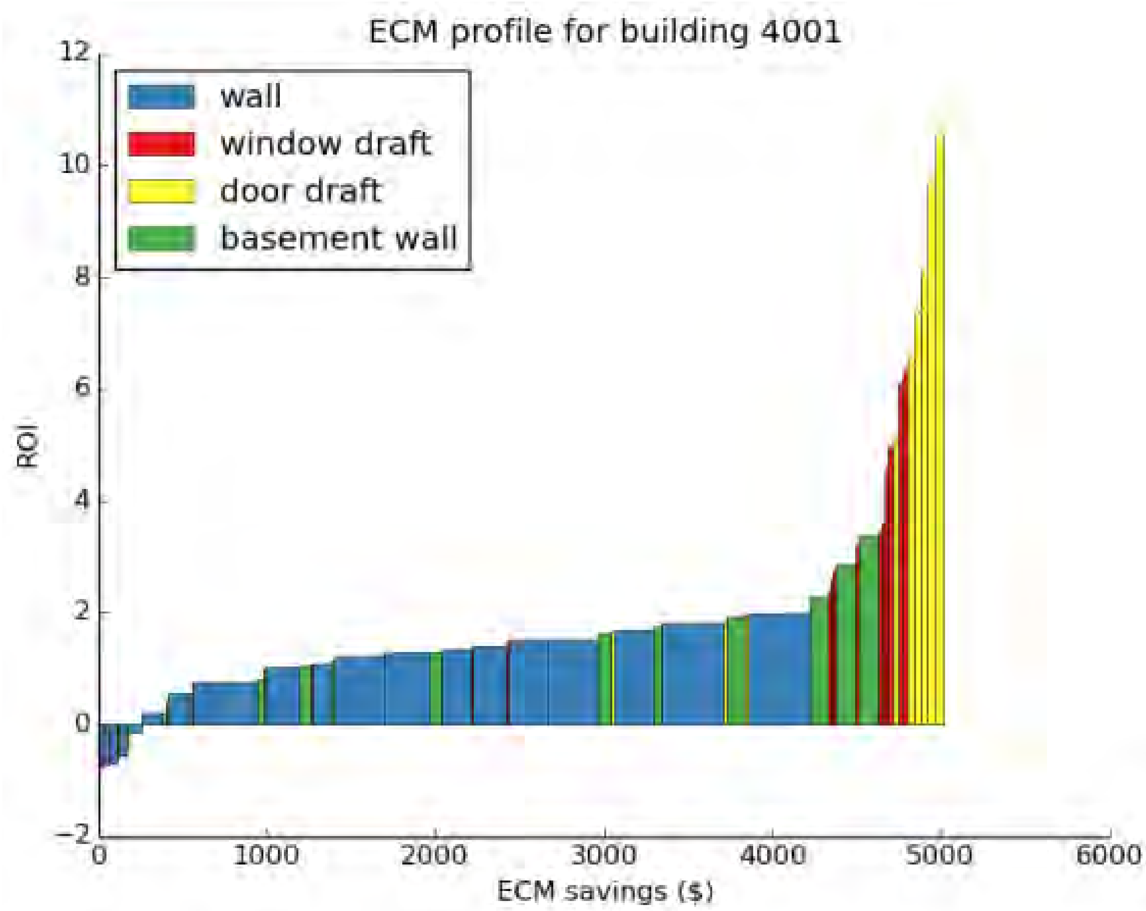


Table 25 lists the recommended envelope ECMs for Bldg 4001, Scott AFB.

Table 25. Envelope ECMs for Bldg 4001, Scott AFB.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Improve Wall Insulation	2316	5580	3422	23078	6.7
Basement Wall Insulation	537	1294	794	4258	5.4
Seal Window Frame Leaks	187	450	276	1118	4.0
Seal Door Frame Leaks	184	443	272	594	2.2

Annual potential remediation savings for this building are $4,764 and total payback is 6.1 years for envelope-related ECMs.

D.26 Bldg 4010

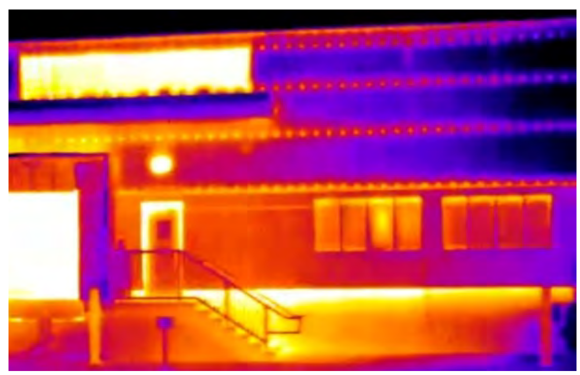
D.26.1 Description of Bldg 4010, Scott AFB

Name: Traffic Mgt F
Use Type: Misc.
Square Footage: 18,753
Avg. Daily Electric Use: Not Provided
Avg. Daily Gas Use: 44.9 therms
Electricity Score: N/A
Gas Score: 90th Percentile
Annual Cooling Load: N/A
Annual Heating Load: 14,835 therms

Bldg 4010 (Figures D-126 and D-127) has a gas usage of 87,416 Btu/sq ft/yr.

Figure D-126. Aerial view of Bldg 4010, Scott AFB.

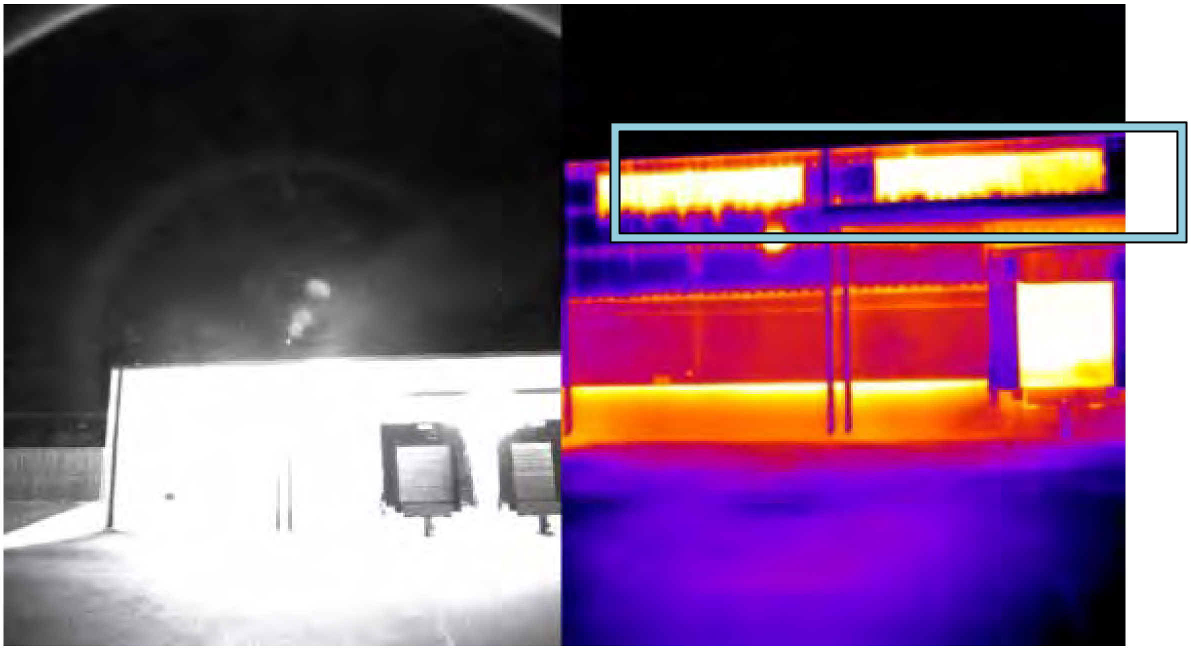
Figure D-127. Thermal image of Bldg 4010, Scott AFB.



D.26.2 Notable leaks at Bldg 4010, Scott AFB

Bldg 4010 (Figure D-128) has some sizable hot patches near the roof line around timestamp 98:29. These may be vents or areas with absolutely no insulation.

Figure D-128. NIR image (left) and thermal image (right) of Bldg 4010, Scott AFB.



The door around timestamp 98:32 has a fairly emissive frame, which indicates air leaks (Figure D-129). The top of the building has a large hotspot that may be caused by a vent.

Figure D-129. NIR image (left) and thermal image (right) of Bldg 4010, Scott AFB. Note the large hotspot near the top of the building.

D.26.3 Envelope ECMs for Bldg 4010, Scott AFB

Figure D-130 shows the relative ROI for envelope ECMs for Bldg 4010, Scott AFB.

Figure D-130. ECM profile for Bldg 4010, Scott AFB.

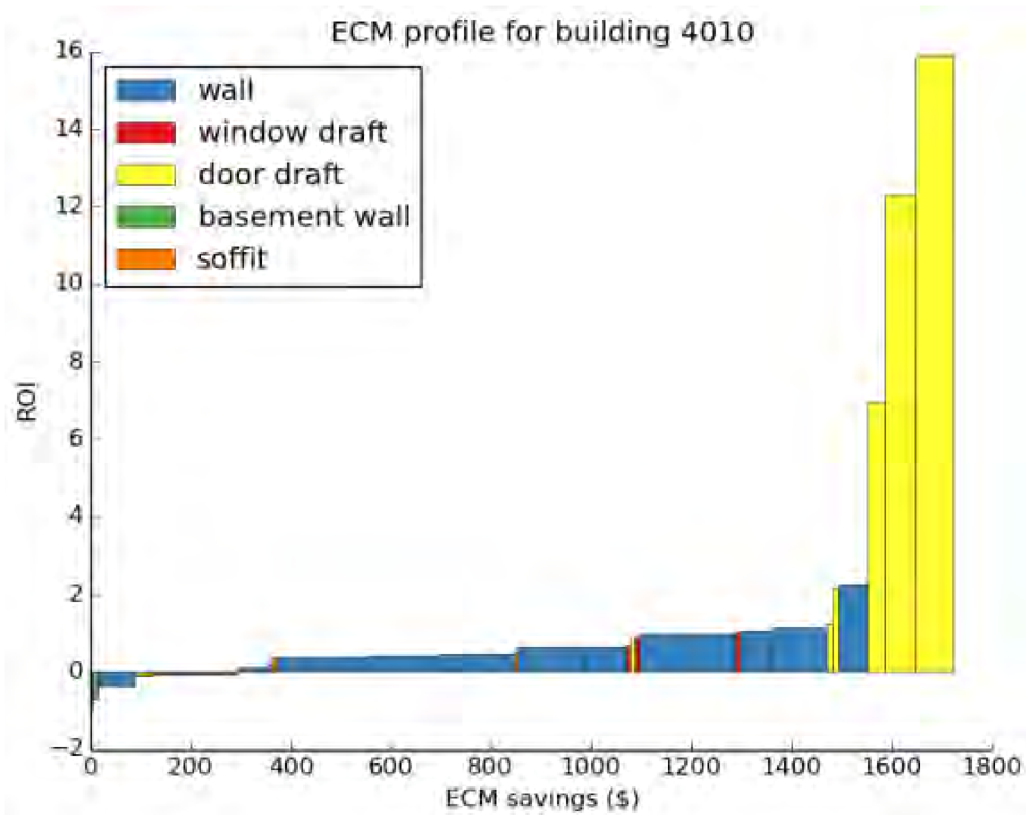


Table 26 lists the recommended envelope ECMs for Bldg 4010, Scott AFB.

Table 26. Envelope ECMs for Bldg 4010, Scott AFB.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Improve Wall Insulation	797	1921	1178	10834	9.2
Seal Door Frame Leaks	136	327	201	398	2.0
Seal Window Frame Leaks	20	49	30	262	8.8
Improve Soffit Insulation	13	31	19	206	10.7

Annual potential remediation savings for this building are $1,428 and total payback is 8.2 years for envelope-related ECMs.

D.27 Bldg 5000

D.27.1 Description of Bldg 5000, Scott AFB

Name: Res Forces Opl Tng
Use Type: Office
Square Footage: 27,720
Avg. Daily Electric Use: 1356.6 kWh
Avg. Daily Gas Use: 45.8 therms
Electricity Score: 65th Percentile
Gas Score: 85th Percentile
Annual Cooling Load: 48,796 kWh
Annual Heating Load: 12,262 therms

Bldg 5000 (Figure D-131 and D-132) has a gas usage of 60,280 Btu/sq ft/yr and electricity usage of 17.9 kWh/sq ft/yr.

Figure D-131. Aerial view of Bldg 5000, Scott AFB.

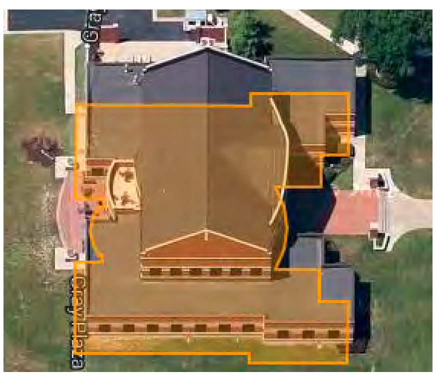
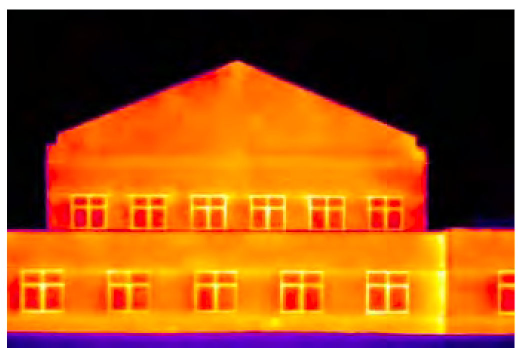


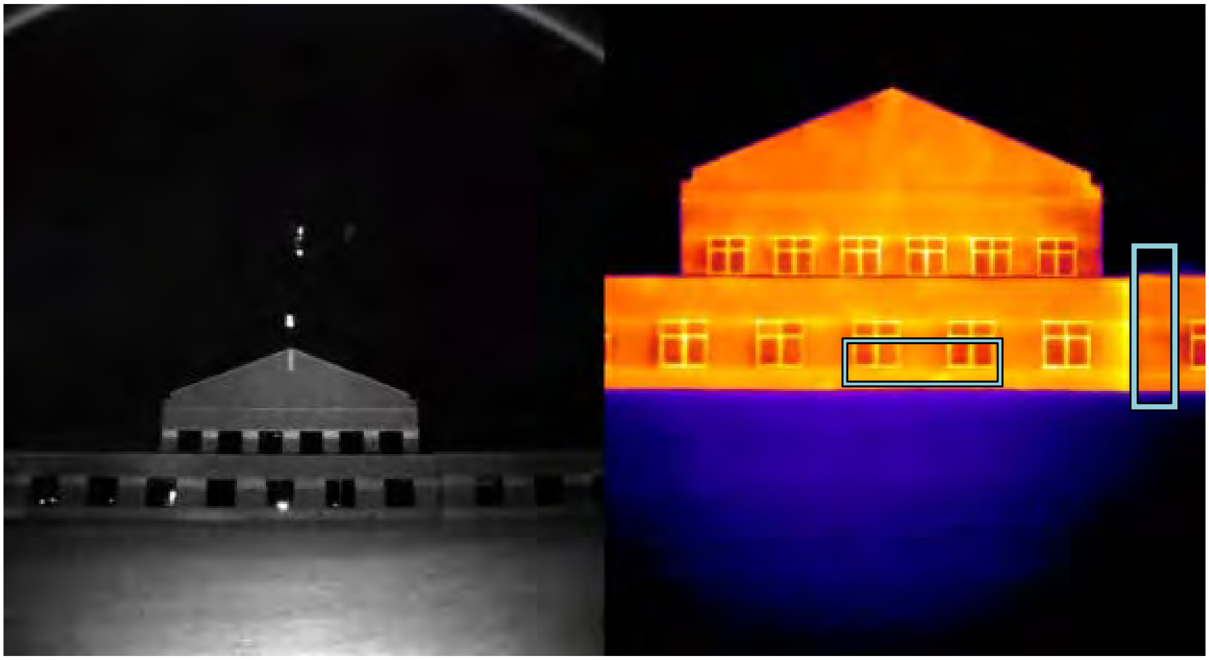
Figure D-132. Thermal image of Bldg 5000, Scott AFB.



D.27.2 Notable leaks at Bldg 5000, Scott AFB

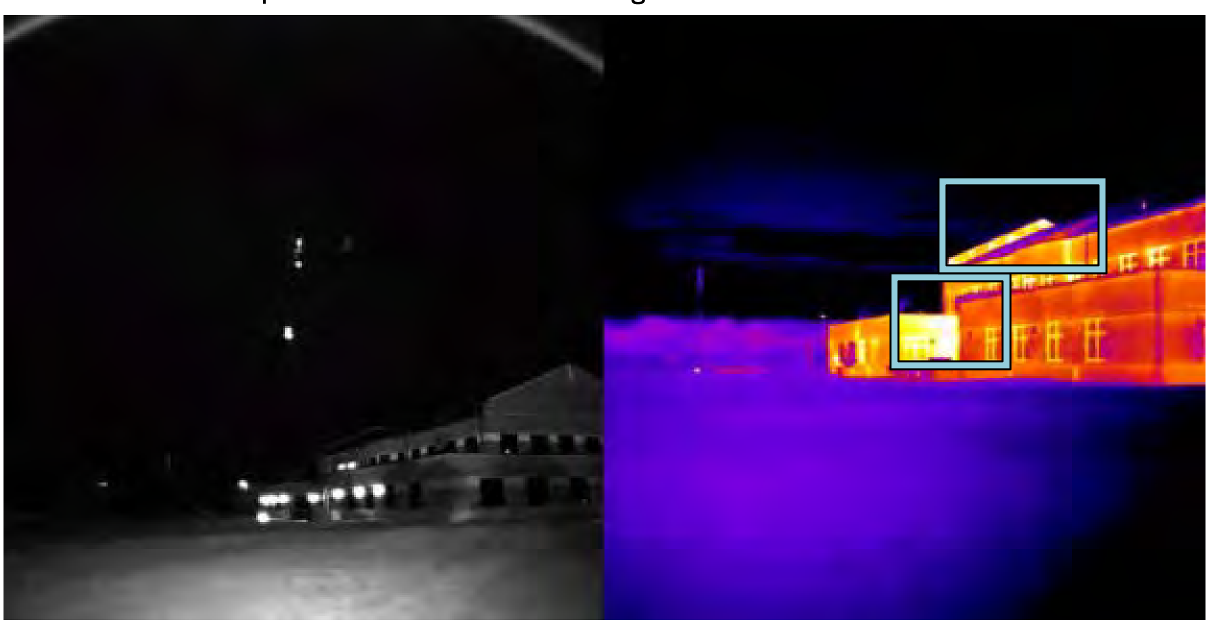
There is a notable vertical hot stripe on the right side of the building, along with a potential thermal bridge above the window frames and some small leaks near the bottom of the wall at timestamp 255:59 (Figure D-133).

Figure D-133. NIR image (left) and thermal image (right) of Bldg 5000, Scott AFB.



There is a notable bright surface along the far wall on the left side of the image, as well as some hot spots above the windows on the right and an emissive roofline at timestamp 256:04 (Figure D-134).

Figure D-134. NIR image (left) and thermal image (right) of Bldg 5000, Scott AFB. Note hot spots above the windows on the right and an emissive roofline.



D.27.3 Envelope ECMs for Bldg 5000, Scott AFB

Figure D-135 shows the relative ROI for envelope ECMs for Bldg 5000, Scott AFB.

Figure D-135. ECM profile for Bldg 5000, Scott AFB.

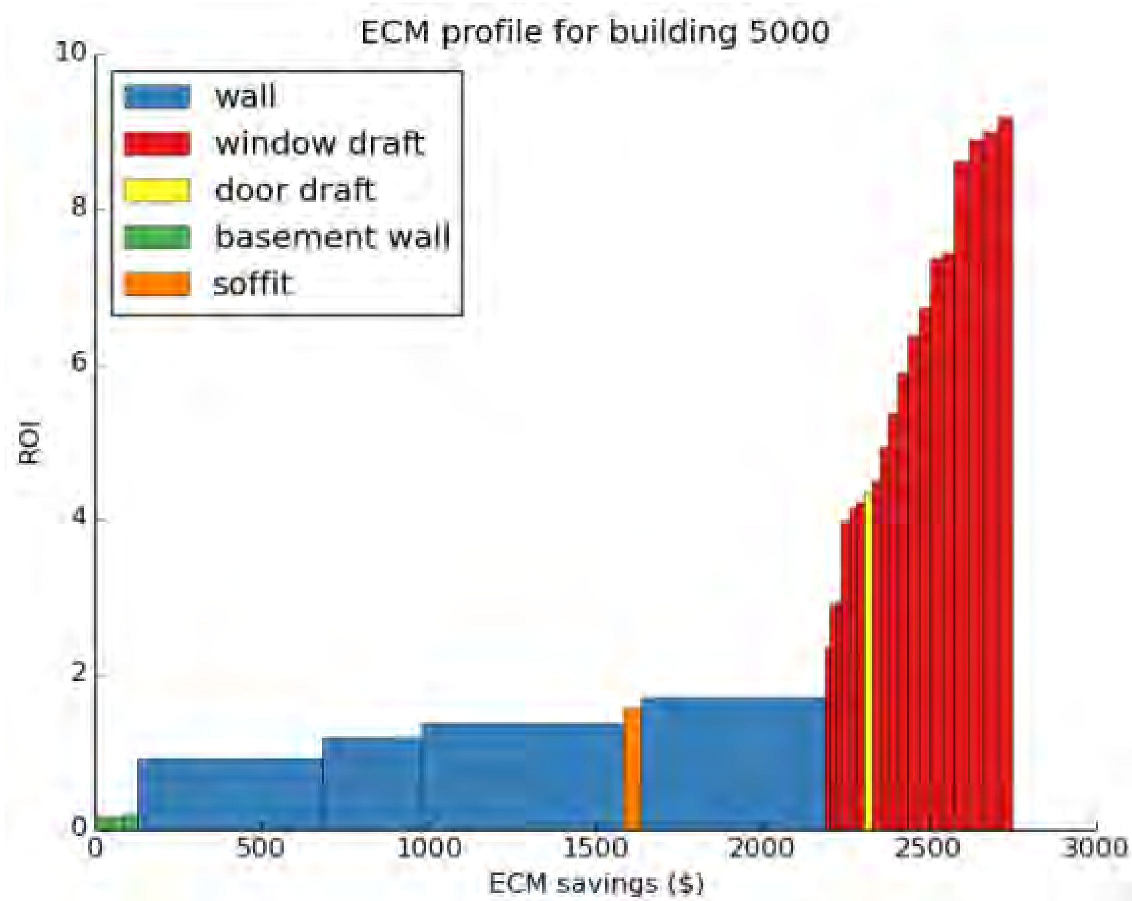


Table 27 lists the recommended envelope ECMs for Bldg 5000, Scott AFB.

Table 27. Envelope ECMs for Bldg 5000, Scott AFB.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Improve Wall Insulation	1360	3276	2009	13328	6.6
Seal Window Frame Leaks	365	879	539	1186	2.2
Basement Wall Insulation	87	211	129	1665	12.9
Improve Soffit Insulation	35	83	51	299	5.9
Seal Door Frame Leaks	16	38	23	66	2.8

Annual potential remediation savings for this building are $2,751 and total payback is 6 years for envelope-related ECMs.

D.28 Bldg 5008

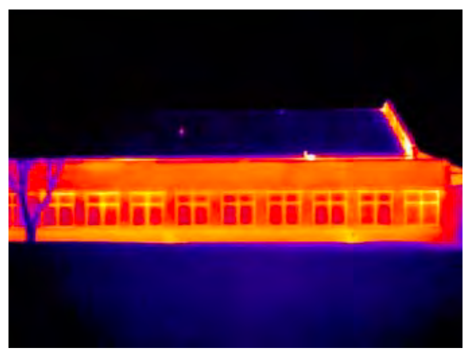
D.28.1 Description of Bldg 5008, Scott AFB

Name: Sq. Ops.
Use Type: Office
Square Footage: 21,913
Avg. Daily Electric Use: 1,677.8 kWh
Avg. Daily Gas Use: 34.2 therms
Electricity Score: 90th Percentile
Gas Score: 75th Percentile
Annual Cooling Load: 71,466 kWh
Annual Heating Load: 9,717 therms

Bldg 5008 (Figure D-136 and D-137) has a gas usage of 56,984 Btu/sq ft/yr and electricity usage of 27.9 kWh/sq ft/yr.

Figure D-136. Aerial view of Bldg 5008, Scott AFB.

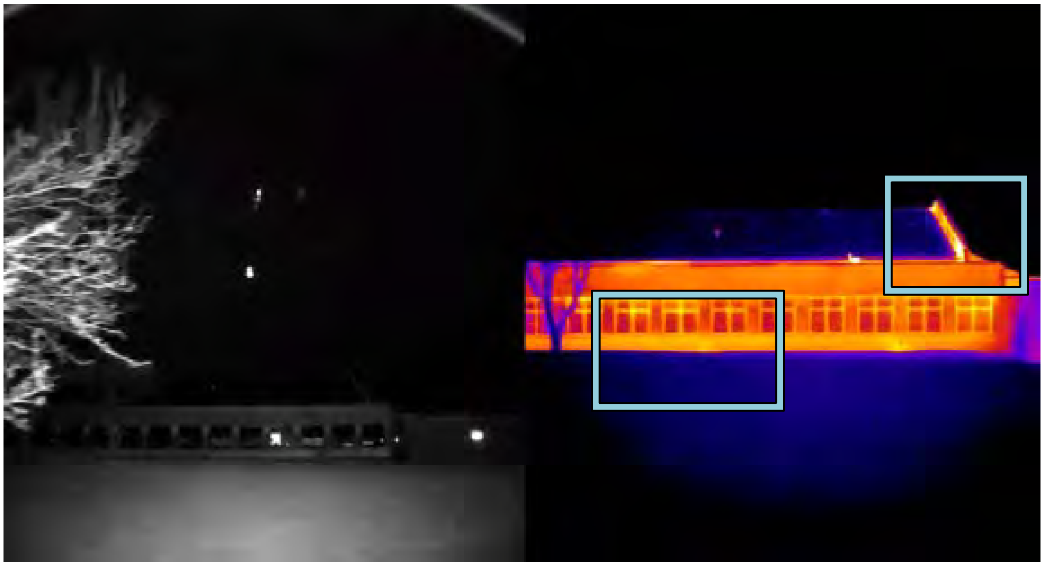
Figure D-137. Thermal image of Bldg 5008, Scott AFB.



D.28.2 Notable leaks at Bldg 5008, Scott AFB

In addition to a generally high-emission wall, there are a number of leaky window frames and a hotspot on the roofline visible at timestamp 255:29 (Figure D-138).

Figure D-138. NIR image (left) and thermal image (right) of Bldg 5008, Scott AFB.



D.28.3 Envelope ECMs for Bldg 5008, Scott AFB

Figure D-139 shows the relative ROI for envelope ECMs for Bldg 5008, Scott AFB.

Figure D-139. ECM profile for Bldg 5008, Scott AFB.

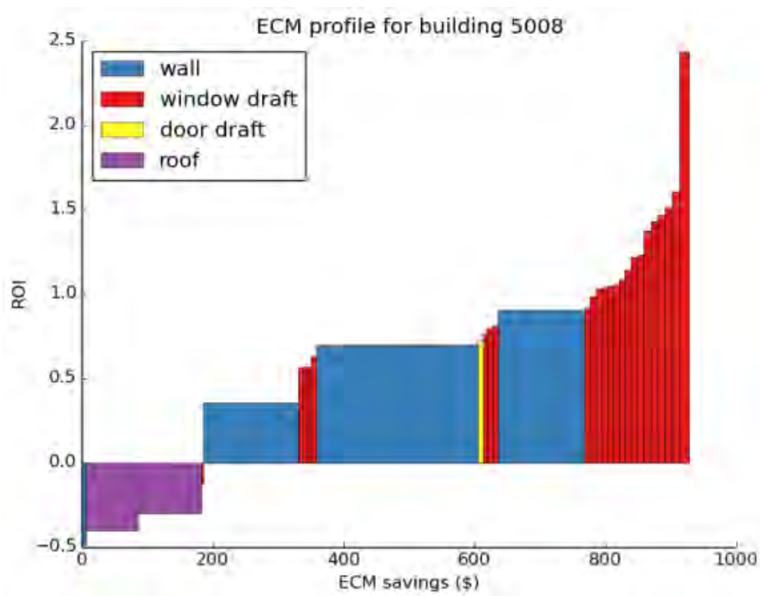


Table 28 lists the recommended envelope ECMs for Bldg 5008, Scott AFB.

Table 28. Envelope ECMs for Bldg 5008, Scott AFB.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Improve Wall Insulation	354	852	522	4819	9.2
Seal Window Frame Leaks	144	346	212	1516	7.2

Annual potential remediation savings for this building are $734 and total payback is 8.6 years for envelope-related ECMs.

D.29 Bldg 5010

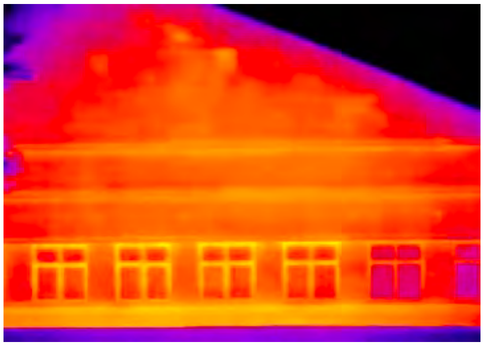
D.29.1 Description of Bldg 5010, Scott AFB

Name: Dh Amn (Det)
Use Type: Misc.
Square Footage: 22,698
Avg. Daily Electric Use: 1,176.6 kWh
Avg. Daily Gas Use: 68.3 therms
Electricity Score: 65th Percentile
Gas Score: 90th Percentile
Annual Cooling Load: 33,988 kWh
Annual Heating Load: 7,316 therms

Bldg 5010 (Figure D-140 and D-141) has a gas usage of 109,751 Btu/sq ft/yr and electricity usage of 18.9 kWh/sq ft/yr.

Figure D-140. Aerial view of Bldg 5010, Scott AFB.

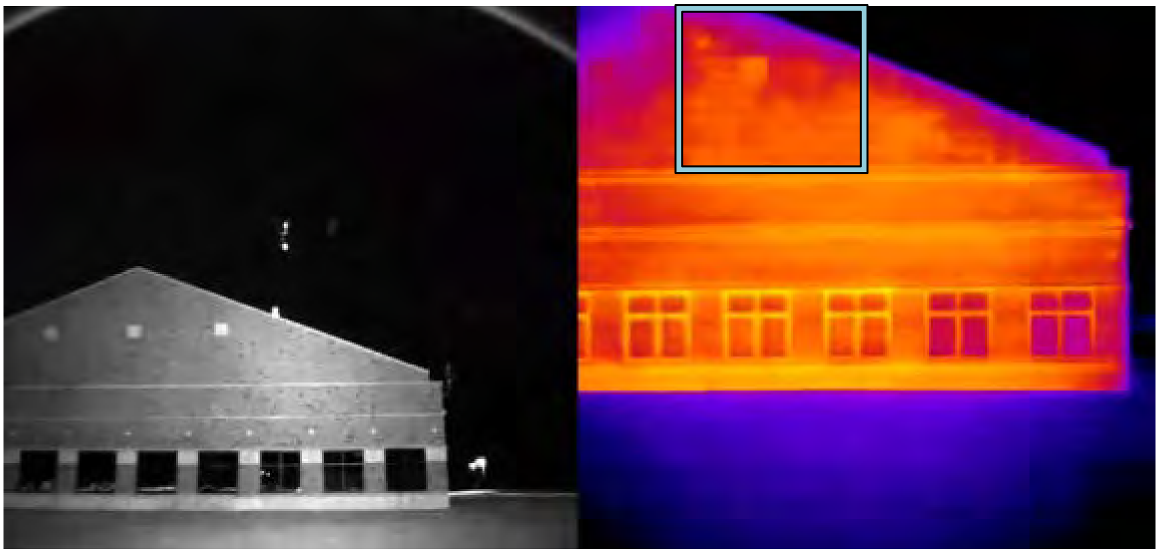
Figure D-141. Thermal image of Bldg 5010, Scott AFB.



D.29.2 Notable leaks at Bldg 5010, Scott AFB

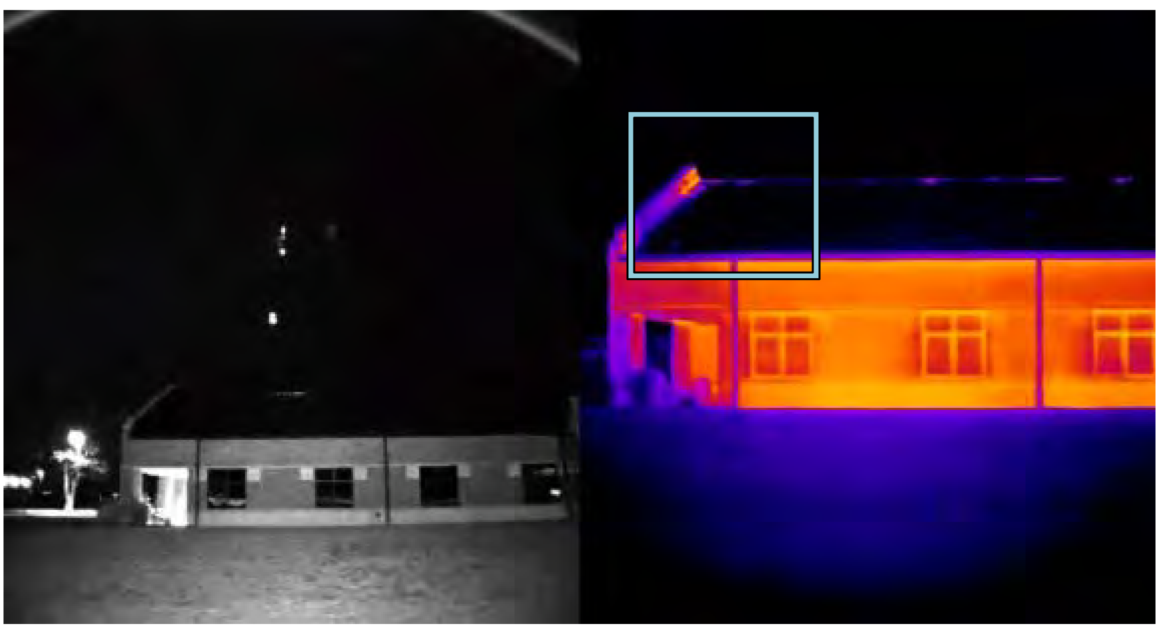
There are a number of splotchy hotspots visible at the top of the wall at timestamp 255:14 (Figure D-142). The wall itself is highly emissive on average, which indicates poor insulation.

Figure D-142. NIR image (left) and thermal image (right) of Bldg 5010, Scott AFB.



There is a noticeable hot strip along the roofline at timestamp 255:17 (Figure D-143).

Figure D-143. NIR image (left) and thermal image (right) of Bldg 5010, Scott AFB.



D.29.3 Envelope ECMs for Bldg 5010, Scott AFB

Figure D-144 shows the relative ROI for envelope ECMs for Bldg 5010, Scott AFB.

Figure D-144. ECM profile for Bldg 5010, Scott AFB.

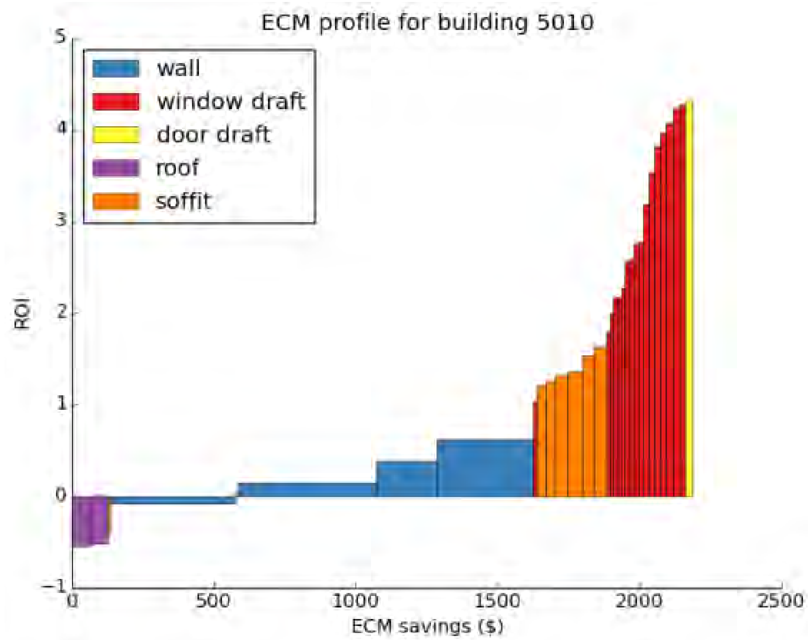


Table 29 lists the recommended envelope ECMs for Bldg 5010, Scott AFB.

Table 29. Envelope ECMs for Bldg 5010, Scott AFB.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Improve Wall Insulation	706	1701	1043	11914	11.4
Seal Window Frame Leaks	196	472	290	1116	3.9
Improve Soffit Insulation	175	422	259	1720	6.7
Seal Door Frame Leaks	16	38	23	65	2.8

Annual potential remediation savings for this building are $1,615 and total payback is 9.2 years for envelope-related ECMs.

D.30 Bldg 5022

D.30.1 Description of Bldg 5022, Scott AFB

Name: Shp Acft Gen Purp
Use Type: Misc.
Square Footage: 45,787
Avg. Daily Electric Use: 1453.9 kWh
Avg. Daily Gas Use: 61.8 therms
Electricity Score: 55th Percentile
Gas Score: 65th Percentile
Annual Cooling Load: 43,624 kWh
Annual Heating Load: 16,628 therms

Bldg 5022 (|Figures D-145 and D-146) has a gas usage of 49,238 Btu/sq ft/yr and electricity usage of 11.6 kWh/sq ft/yr.

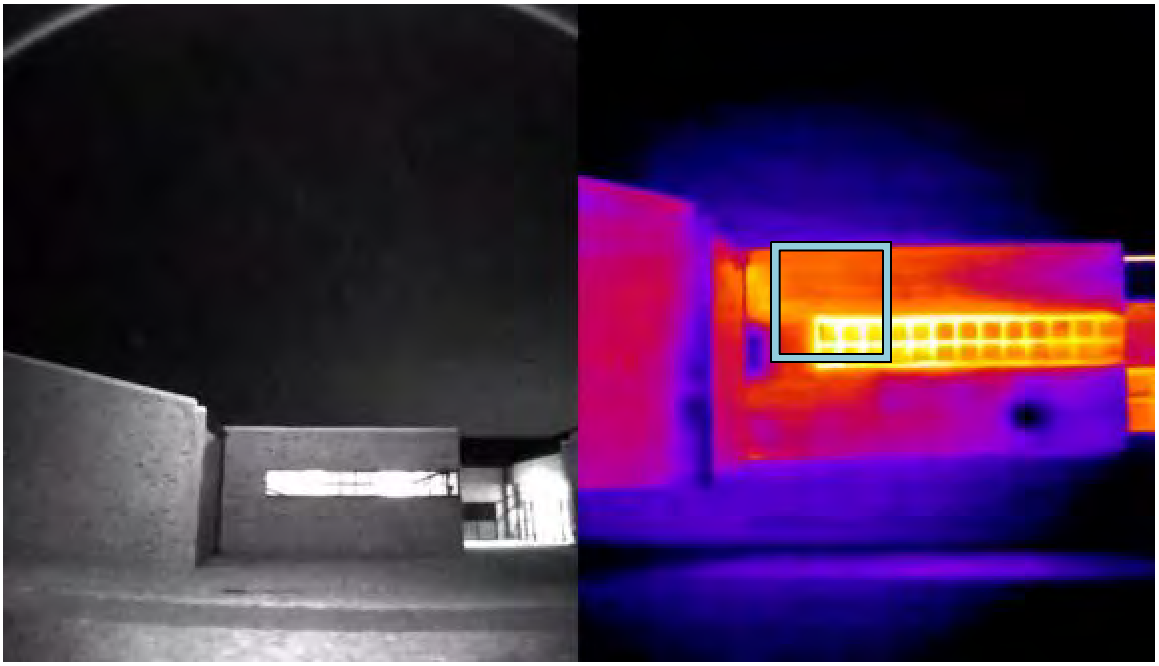
Figure D-145. Aerial view of Bldg 5022, Scott AFB.

Figure D-146. Thermal image of Bldg 5022, Scott AFB.

D.30.2 Notable leaks at Bldg 5022, Scott AFB

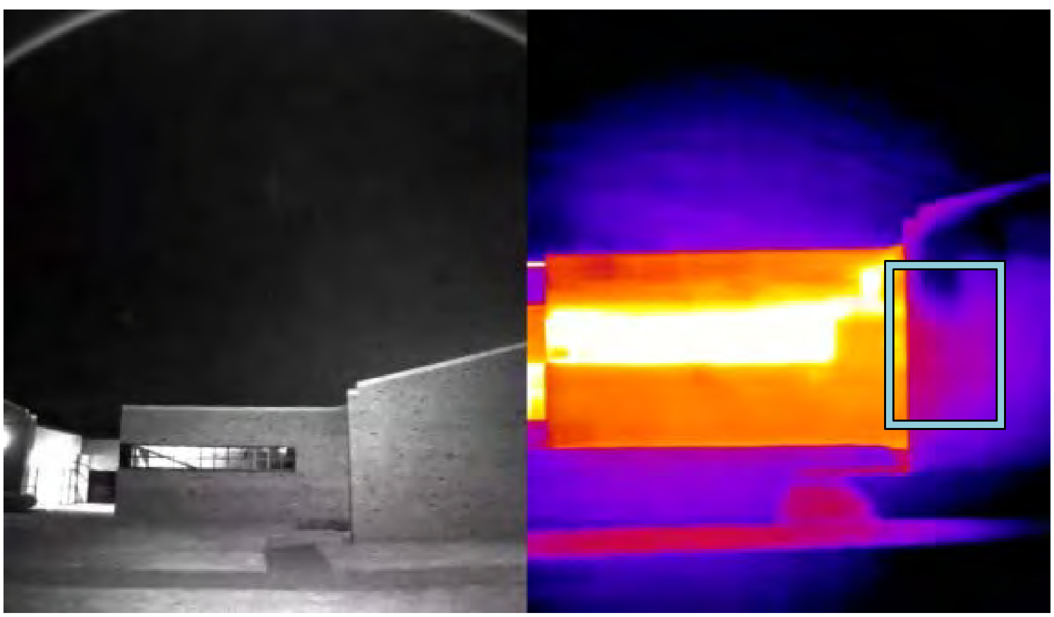
There is a hotspot visible to the left of the windows on the wall at timestamp 117:43 in the Drive-By Tool (Figure D-147).

Figure D-147. NIR image (left) and thermal image (right) of Bldg 5022, Scott AFB.



A similar highly emissive spot can be found to the right of the windows on the wall at timestamp 117:49 (Figure D-148).

Figure D-148. NIR image (left) and thermal image (right) of Bldg 5022, Scott AFB. A highly emissive spot can be found to the right of the windows on the wall.



D.30.3 Envelope ECMs for Bldg 5022, Scott AFB

Figure D-149 shows the relative ROI for envelope ECMs for Bldg 5022, Scott AFB.

Figure D-149. ECM profile for Bldg 5022, Scott AFB.

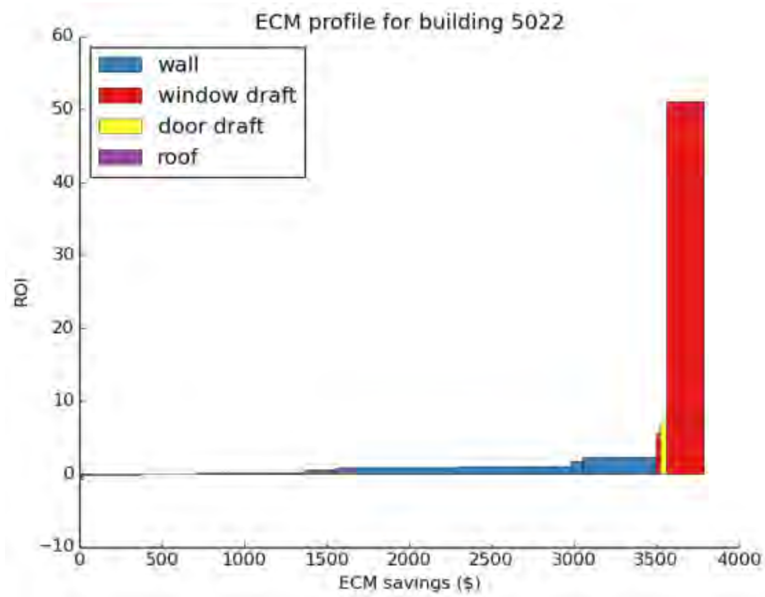


Table 30 lists the recommended envelope ECMs for Bldg 5022, Scott AFB.

Table 30. Envelope ECMs for Bldg 5022, Scott AFB.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Improve Wall Insulation	1876	4521	2773	23670	8.5
Seal Window Frame Leaks	173	418	256	131	0.5
Seal Door Frame Leaks	24	58	36	66	1.8
Improve Roof Insulation	15	36	22	277	12.6

Annual potential remediation savings for this building are $3,086 and total payback is 7.8 years for envelope-related ECMs.

Appendix E: Remediation Cost Estimates

This appendix provides details on the approaches used to estimate mitigation costs associated with window frame sealing, door frame sealing, wall insulation, and roof insulation. For the purposes of this analysis, it was assumed that soffit insulation shares the same characteristic costs as roof insulation, as soffit-specific remediation costs were not readily available. All of these calculations use a standard labor cost per hour, L_{cost}, which is assumed to be $60.

E.1 Window frame sealing

The cost of window frame sealing can be modeled as:

$$C_w = W_{num} \cdot M_{window} + L_{cost} \cdot \frac{W_{time}}{60} \tag{E-1}$$

where:

W_{num} is the number of windows sealed
M_{window} is the material cost per window sealed, assumed to be $33 (Homewyse 2014a)
W_{time} is the labor time required per window sealed, assumed to be 37 minutes (Homewyse 2014a).

This resulted in a typical window sealing cost of $70 per window, assuming that enough windows will be sealed during a single trip that other time costs (e.g., travel time) will be negligible.

E.2 Door frame sealing

Doorframe sealing and weather-stripping is calculated similarly to window frame sealing:

$$C_d = D_{num} \cdot \left(M_{door} + L_{cost} \cdot \frac{D_{time}}{60}\right) \tag{E-2}$$

where:

D_{num} is the number of doors sealed
M_{door} is the material cost per door sealed, assumed to be $14.9 (Homewyse 2014b)
D_{time} is the labor time required per door sealed, assumed to be 57 minutes (Homewyse 2014b).

This results in a typical door sealing/weather-stripping cost of $72 per door.

E.3 Wall insulation

Wall insulation costs are comprised of access time, installation time, insulation costs, and other material costs related in the equation below:

$$C_w = W_{sqft} \cdot M_{wall} + L_{cost} \cdot \left(\frac{W_{sqft}}{W_{rate}}\right) \tag{E-3}$$

where:

W_{sqft} is the square footage of the wall in question

M_{wall} is the material cost per square foot of insulation installed, assumed to be $2.87 (PNNL 2011a)

W_{rate} is the square footage of wall insulation that can be installed in an hour by a single worker, including preparation and access time, assumed to be 13 (PNNL 2011a).

For a 100 sq ft section of poorly insulated wall, this would amount to a total cost of $784.

E.4 Roof insulation

Roof insulation costs are calculated similarly to wall insulation costs, and are comprised of access time, installation time, insulation costs, other material costs, and fixed material costs related in the equation below:

$$C_r = R_{sqft} \cdot M_{roof} + L_{cost} \cdot \left(\frac{R_{sqft}}{R_{rate}}\right) \tag{E-4}$$

where:

R_{sqft} is the square footage of the roof in question

M_{roof} is the material cost per square foot of insulation, assumed to be $2.66 (PNNL 2011a) (PNNL 2011b).

R_{rate} is the square footage of roof/ceiling insulation that can be installed in an hour by a single worker, including preparation and access time, assumed to be 11.5 (PNNL 2011a).

For a 100 sq ft section of poorly insulated roof, this would amount to a total cost of $788.

Appendix F: Collected Data Sample

Data Description: Essess collected terabytes of data at each base. Below is an example summary data file for 14 seconds of Essess data. Green text is the system data file and the black text is the explanation of what was actually happening in the system.

Sample Data:
path: 2014-02-22-19-16-22_7.bag
version: 2.0
duration: 14.0s
start: Feb 22 2014 19:16:22.46 (1393114582.46)
end: Feb 22 2014 19:16:36.50 (1393114596.50)
size: 2.0 GB
/diagnostics
System Diagnostic Information
/driver_bottom_camera/camera_info
Camera Information & Intrinsics
/driver_bottom_camera/color_remapped
8bit color image remapped from 16bit mono image data
/driver_bottom_camera/flir_info
FLIR thermal coefficients and hardware information
/driver_bottom_camera/image_info
Image Statstics
/driver_bottom_camera/image_raw
Raw 16bit Image Data
/driver_bottom_camera/image_raw_throttle
2Hz Throttled Raw 16bit Image Data
/driver_nir/camera_info
Camera Information & Intrinsics
/driver_nir/hardware_info
Camera hardware information
/driver_nir/image_info
Image Statstics
/driver_nir/image_raw
Raw 16bit Image Data
/driver_nir/image_raw_throttle
2Hz Throttled Raw 16bit Image Data

/driver_nir/reduced_and_throttled
2Hz Throttled 8bit Image at half resolution
/driver_top_camera/camera_info
/driver_top_camera/color_remapped
/driver_top_camera/flir_info
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14. ABSTRACT
Each year, U.S Air Force buildings waste millions of dollars' in energy lost through leaks in building envelopes. Identifying the source of this wasted energy has historically been time consuming and prohibitively expensive for large-scale energy analysis. This work used an independently developed drive-by thermal imaging solution that can enable the Air Force to achieve cost-effective energy efficiency at much greater scale than other commercially available techniques of measuring energy loss due to envelope inefficiencies from the built environment. A multi-sensor hardware device attached to the roof of a customized vehicle was used to rapidly scan hundreds of buildings in a short period of time.

At Scott Air Force Base, the unit identified over 3,000 distinct building feature components (doors, windows, soffits, etc.) on buildings across the base. These features were categorized by type and surface temperature to provide an in-depth analysis of each building's envelope energy profile. This report includes an in-depth analysis of 30 buildings at this installation, recommends specific energy conservation measures (ECMs), and quantifies significant potential return on investment.

15. SUBJECT TERMS
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